The DTIC Review

Land Mine Warfare: Detection and Clearance

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Telephone: (703) 767-8274, DSN: 427-8274
FAX: (703) 767-9070
Email: bibs@dtic.mil

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Land mines have become an integral part of twentieth century warfare; but unlike other weapons, blind terrorism remains long after the war. This compilation of citations highlights the major technological efforts presently available or being developed in the world of land mine warfare, mine detection, and mine clearance from the Defense Technical Information Center (DTIC). The authors of the following papers describe the nature of many varieties of both plastic and metal land mines and the measures being developed to clear them in a safe humanitarian manner.

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FOREWORD

This is the second issue of *The DTIC Review*. For this issue, the editors have selected the topic: *Land Mine Warfare: Detection and Clearance. The DTIC Review* brings its readers the full-text of selected technical reports and a bibliography of other references of interest under one cover. This format provides our readership with a sampling of documents from our collection on a particular topic of current interest. The editors hope that you find this effort of value and appreciate your comments.

Kurt N. Molholm
Administrator

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INTRODUCTION

Land mines have become an integral part of twentieth century warfare; but unlike other weapons, blind terrorism remains long after the war. The situation is very alarming. Presently, over 100 million mines are in place in over sixty-four countries. Twenty new mines are planted for every mine that is removed.

Not only is the presence of mines an obstacle to the establishment of a durable peace, but also, every month 500 to 800 people (mostly civilians) are killed by mines and about 2,000 are maimed. The statistics represent a cost to human life that is greater than that of ballistic missiles and nuclear weapons combined.

This compilation of citations highlights the major technological efforts presently available or being developed in the world of land mine warfare, mine detection, and mine clearance from the Defense Technical Information Center (DTIC). The authors of the following papers describe the nature of many varieties of both plastic and metal land mines and the measures being developed to clear them in a safe humanitarian manner.

These documents are only a sampling of the information available on land mine technology from DTIC's extensive collection on the subject. At the end of the volume you will find a section on relevant electronic sources available on the Internet as well as additional references. In depth literature searches may be requested by contacting the Reference and Retrieval Division at the Defense Technical Information Center on (703) 767-8274, DSN: 427-8274, FAX: (703) 767-9070, or Email: bibs@dtic.mil.

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Sensors for the Detection of Land-Based Munitions

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By
A.J. Healey and W.T. Webber

September 1995

Dept of Mechanical Engineering
Naval Postgraduate School, Monterey, CA

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

SENSORS FOR THE DETECTION OF LAND-BASED MUNITIONS

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

Rear Admiral M.J. Evans
Superintendent

R. Elster
Provost

This report was prepared for NAVOEDTECHDIV, Indian Head, MD.

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The report was prepared by:

A.J. Healey
Professor
Department of Mechanical Engineering

W.T. Webber

Reviewed by:

Matthew D. Kelleher
Chairman
Department of Mechanical Engineering

Released by:

Paul J. Marto
Dean of Research

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13. ABSTRACT

This report provides a summary of current land-based munition detection sensor development. Sensors are categorized based upon the principle of their operation: electromagnetic, conductive, mechanical, optical, acoustic, and chemical. Each category is subdivided into particular operational sensor types. Theory of operation for each particular sensor type is provided, as well as a discussion of advantages and disadvantages of each. A discussion of sensor performance is included. The final section of the report is a survey of commercialy available munition detection sensors along with comments concerning their performance.

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ABSTRACT

This report provides a summary of current land-based munition detection sensor development. Sensors are categorized based upon the principle of their operation: electromagnetic, conductive, mechanical, optical, acoustic, and chemical. Each category is subdivided into particular operational sensor types. Theory of operation for each particular sensor type is provided, as well as a discussion of advantages and disadvantages of each. A discussion of sensor performance is included. The final section of the report is a survey of commercialy available munition detection sensors along with comments concerning their performance.

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Sensors for the Detection of Land-Based Munitions

I. Introduction.

There is a serious problem facing both third world and developed nations around the globe. This problem affects the use of land for agriculture, transportation and housing. It is encountered in any place where wars have been fought, or ordnance used, in the last 100 years. The problem is one of unexploded ordnance. The ability of unexploded ordnance to disrupt peaceful use of land (and water) resources is enormous. The effects of unexploded ordnance are only currently being realized. For instance:

-The United Nations estimates that there are more than 100 million land mines currently placed in regional conflicts throughout the world. Effective, deadly, easy to use and cheap (prices currently in the range of 3-5 dollars apiece) popularity of landmine warfare is increasing.
In contrast, clearance of mines by trained personnel is estimated to cost $200 each, resulting in a growing inventory of mines in use. [Walker, 1995]

- Following the end of the Cold War, Congress has begun to take inventory of many former test and training ranges, with the idea of eventually returning them to peaceful use. The problem of locating, and then disposing of, the myriad forms of unexploded ordance located on these ranges, (and in unmarked locations on many bases) must be solved.

- Throughout the world, people continue to find remnants of ordnance left from previous conflicts. This ordnance is still "live" in a surprising number of cases. WWII ordnance, alone, has presented range clearance problems, within the last five years, in locations as varied as Guam, Hawaii and San Diego.

- Finally, current technology allows the placement of hundreds of submunitions by a single 1000 pound bomb package. Detection and disposal of these munitions during peacetime range clearance, and following actual battles must also be addressed.

The task of dealing with the practical aspects of removing fired or armed ordnance belongs to the military's Explosive Ordnance Disposal (EOD) technicians, who are supported by the EOD Techinical Division, Indian Head, Maryland. It is there that the equipment and procedures which will be used by the EOD technician to detect, identify, recover and dispose of unexploded ordnance are developed. The scope of this undertaking is enormous, as the plethora of weaponry developed by countries around the world for use in all environs is difficult to imagine.

In this paper we will concentrate on just one specific tasking-a survey of the sensors which can be used in the detection of land based munitions. This effort is, in itself, a significant undertaking, given the recent advances in sensor manufacturing, particularly microprocessor technology used in data processing.

II Historical Perspective.

The detection of submunitions, landmines, bombs, projectiles and various other land-based munitions has been historically accomplished by trained personnel employed in some type of sweep scenario.

Surface ordnance was ordinarily easily detected visually, although in many areas, plant growth posed such difficulties that controlled burns were used to increase probability of detection. The time consuming process of lining up sweep troops, under the supervision of EOD technicians, and conducting large scale area clearance on foot, is still used frequently.

The problem of detecting buried, or hidden, munitions is another matter entirely. Prior to electronic metal detectors, buried bombs and projectiles were located by observing the geometry of entrance penetrations and "guessing" the location of their final resting place. The munition was then actually detected by digging to its location. The ability to accurately predict the behavior of an impinged bomb or projectile was not (and still is not) very good. Their behavior resulted in lots of earth being moved prior to location. Landmines were pursued in a more gentle fashion using probes and hand excavation by trained personnel (another method still used occasionally.)

With the advent of rudimentary magnetic detectors, large ferrous munitions could be located or localized for excavation. Lots of non-ordnance was still located, and cluttered up the scene, but excavation efforts were reduced. Within the last 20 years, additional advances produced metal detectors which were capable of sensing conductive metal of many types, and munitions of lesser size. All of these detectors were essentially man-carried and had corresponding slow clearance rates.

This brings us to present day and the current crop of new technology. These devices are capable of using all manner of physical properties and scientific advances. They can often be used on a variety of platforms including aircraft, vehicles, as well as being man-carried. These attributes are important because, just as the sensors for ordnance hunting have improved, so has the ordnance, itself. Sensitivities have been increased, firing mechanisms are more advanced and materials used in their construction include much less ferrous metal than in the past.

III. Sensor Overview

In order to make an intelligent decision concerning the possible use of a specific sensor for a particular problem, it is essential that the theory of operation of the sensor, its limitations, and the conditions which might affect its performance, are fully understood. In conducting this overview of sensor technology we have divided the sensor types into six major categories based upon the principle of their operation. These major categories are: electromagnetic, conductive/resistive, mechanical, optical, acoustic, and chemical. Examining each of these categories, separately, we will discuss the theory behind the operation of each individual sensor types and then later address specific systems which use them.

At this point it is prudent to inject one additional note concerning sensors and their use. Many manufacturers and contractors are currently using improvements in microprocessor design to incorporate a number of sensor types into a single detection system. These suites of hybridized sensors are, in general, superior to a single sensor arrangement. There is an inherent difficulty, however, in attempting to survey and classify the effectiveness of the myriad combinations of sensor packages which may be derived in this fashion. The end effectiveness of these systems is determined, in large part, by the treatment of the sensor data and evaluation by trained users. For this reason, the scope of this paper will be limited to single sensor systems, which are defined as requisite sense heads/arrays and the electronics which support the conversion of sensor data to indicate ordnance presence.

IV Electromagnetic Sensors

This sensor category uses some form of electromagnetic property or energy in order to function.

1. Electromagnetic Field

Theory- The earth's magnetic field is generally constant within a local area, with a strength of approximately .5 gauss (1 gauss= 100,000 gamma 1 Tesla=10,000 gauss.) The majority of the field is derived from variation in spin rates between the earth's core and mantle. It can be roughly represented by a large dipole which passes through the earth's center and is about 11 degrees displaced from the earth's axis of rotation. A magnetometer is a sensor which is designed to measure this field. There are two main variations among magnetometers. These are total field magnetometers and vector magnetometers. The first is a non-directional device which produces an output which is a function only of the total magnetic field passing through the device. The latter measures only the component of the magnetic field which lies parallel to their sensitive axis. Total field magnetometers include proton precession and optically pumped magnetometers. Vector magnetometers include flux gate, Hall effect and magnetorestrictive magnetometers. [Fraden, 1993]

a. proton precession-uses fluid (usually water) which is placed in a container within a solenoid, the axis of which is aligned at right angles to the magnetic field under investigation. A polarizing field is developed when the solenoid is energized. This aligns the magnetic spin axis of the water's protons perpendicular to that of magnetic field. When the polarizing field is instantaneously removed, the protons begin to precess about the axis of the magnetic field under investigation. A voltage, proportional to the magnetic field strength, is induced in the solenoid. This voltage can be amplified and measured. Capable of 10 readings per second with resolution to 1 nanoTesla. [Bartington, 1994] pros: very sensitive, is used as the common calibration standard. Can be ganged for use as a gradiometer which is well suited to airborne platforms.

cons: somewhat slow (Overhauser effect used to improve response speeds), large size and power, useful only with ferrous metals.

b. optically pumped-light from a cesium metal vapor lamp is circularly polarized and directed along the approximate axis of the magnetic field to be measured. Light passes through an absorption cell containing vapor of the same metal. The intensity of the emerging beam is monitored using a photocell. Its intensity is indirectly proportional to magnetic field strength. (Zeeman splitting phenomena) [Bartington, 1994]

Pros: very sensitive-10 pico Tesla, fairly rugged.

Cons: Large power requirements. must be aligned within 45 degrees of magnetic field or multiple sensors ganged to provide coverage. Limited life of approximately ten years.

c. flux gate. - These magnetometers use a specific property of magnetic flux to determine the local field strength. By using an exciting coil to drive a highly permeable metal core in and out of a condition of saturation (using a square voltage waveform of sufficient magnitude,) magnetic flux lines in the core area are pulled into or out of the core. At saturation, the core inductance falls rapidly and current levels spike to DC resistance limited levels. A separate sensing coil will detect these movements by the resultant induced current spikes and, using circuitry, compare their phase, polarity, and size, to that of the local "null" field used in calibration. Using two parallel toroidal cores with opposed excitation windings with a single overwound pickup coil produces cancellation of all but desired phase varying signals attributed to the external field. Output via a low pass filter is a DC or slowly varying voltage which reflects external field behavior. Currently the **most popular magnetometer design.**

Sensitivity: 12 mV/gauss

Pros: Accurate measurement of weak magnetic fields, small low power, relatively simple, robust circuitry and materials.

Cons: Useful only on ferrous metals at small ranges. [Fluxgate Magnetometry, 1991]

d. Hall effect. - This sensor is based upon the fact that a moving electric carrier (electron) will experience a force produced by a magnetic field which intersects its path of travel. Using a thin strip of metal through which a current is passed in the longitudinal direction, voltage readings are established in the same plane, but at a perpendicular. As the strip is passed through magnetic fields, and lines of flux pass orthogonally through the strip, electrons are displaced toward one side of the strip. The resultant voltage potential between sides of the strip relate the strength of the magnetic field. [Fraden, 1993]

Pros: Simple, rugged, established method,

Cons: Relatively large voltages required. Limted to use with ferrous metal targets.

e. Magnetorestrictive.

Theory- Some materials have been found to vary in their resistance to electric current as the strength of the magnetic field in which they are located varies. Using two magnetoresistors, having this property, in opposing Wheatstone bridge configuration, along with two shielded magnetoresistors will yield a circuit which provides voltage output based upon magnetic field strength changes. [Brown, 1995]

Sensitivity: 10^-6 gauss (2.5 mV/gauss)

Pros: small, sensitive, low power

Cons: ferrous metals only, relatively new technology

2. Inductance

Theory- The term inductance implies the magnetic flux coupling of two coils, one of which provides the driving field. In common use, the inductance sensor uses a reference coil to produce a magnetic field which in turn induces eddy currents in any conductive material through which it passes. Two pickup methods may be used. In the first, a second sensing coil detects the presence of magnetic fields that result from the induced eddy currents in the targets. In the second, the sensor is a tuned circuit which uses AC voltage driven at a frequency based upon an LC characteristics inherent within the device. When the circuit is disrupted by increased mutual inductance from a target, the circuit voltage drops, providing an indication of target presence.

The sensor can detect most conductive substances, not just ferrous metals. Pulsed induction sensors have been in use since the 1970's for ocean salvage operations. There is a physical limitation inherent in the sensor detection range as range falls away at a rate of 1 /r^6 (r-radius of sensor coils.). [TR-311, 1993, McFee, 1984]

Pros: Robust systems capable of being fielded in small packages with low power requirments. Useful in detecting all conducting materials.

Cons: Relatively short range, will not detect plastics.

3. Ground Penetrating Radar (GPR)

Theory- Electromagnetic radiation is emmitted into the ground where it may be absorbed or reflected from a target surface. The characteristic of the reflected signal is dependent upon the radar signal used, soil dielectric constant (which is in turn dependent upon soil makeup and moisture), and the material which makes up the target. Smooth surfaced metallic targets reflect energy most efficiently. Microprocessing of target returns, time of signal flight, phase polarization, amplitude time delay and propagation direction, yields information on target type and location. All GPR systems are limited by high moisture content in soils, reliance on metalllic or air/plastic interfaces which must provide sufficient return for detection, and energy loss at the air/surface interface. Four categories of GPR, based upon transmission characteristics, have been established. Large bandwidth, pulse radars are currently popular. Microprocessor use in synthetic aperture processing into plan or 3-D images is an important detail in reducing current high false positive rate. Resolution: at high frequencies (of approximately 1 GHz) depth resolution in the 1-3 centimeter range is possible. Poor angular resolution of approximately 60 degree arcs results unless synthetic aperture techniques are applied. **Soil type is probably the over-riding variable in any GPR performance.** [TR-311, 1993, Herman, 1994]

a. short pulse radar Frequency band: 30 Mhz to 2 Ghz

Pros: High frequency results in good depth resolution

Cons: Limited to short range use.

b. video pulse radars. Frequency band: dc to 3 Ghz .

Pros: large bandwidth provides good target information with minimal signal interference.

Cons: Difficult to separate/interpret large variety of frequency returns.

c. Step frequency radar: uses continuous wave radar, stepped in frequency based upon the phase return of relected waves.

Pros: Effectively selects low vs. high frequency transmissions to optimize resolution and penetration.

Cons: Lacks depth of penetration, best suited for shallow use.

d. frequency modulated continuous wave radar: single/discrete number of operating frequencies.

Pros: Using synthetic aperture techniques/microprocessing provides excellent holographic images.

Cons: Very sensitive to changes in soil conductivity and height of antennae above ground. Somehwat slow. Requires large processing abilities.

4. X-ray Backscatter.

Theory-pulsed x-ray radiation is directed into the soil where it can impinge upon targets and can be reflected back to a receiver. Backscatter levels obtained from a clean area are compared to that received from the sweep area to determine target presence. The key issue involved here is that the electron density of a material affects its ability to scatter x-ray radiation. Plastics generally have low atomic numbers and are good scatterers. Difference in scattering properties between plastic and soil provide the contrast required to image (Compton Backscatter Imaging.) [TR-311, 1993, Keshavmurthy, 1995]

Pros: high frequencies results in good target resolution, works on plastic.

Cons: High energy use; high frequencies result in shallow detection ranges.

Note: Additional work is being done with x-rays to ascertain feasibility of fluorescence or emmission of other energy in sufficient levels to allow detection, following concentrated x-ray irradiation of plastic explosives.

V. Conductivity/resistivity.

Theory- Using a system of portable transmitter and receivers an area of ground can be surveyed for variation in its ability to conduct current. By using an exciting field to induce eddy currents in the soil, measurements of the eddy current magnetic field will provide an indication of the soils conductivity. By establishing a baseline standard in a clean area prior to searching, changes in conductivity in the soil which may result from conducting substances such as mines can be detected. The system does not target specific mines but plots gradations in soil resistivity. A typical dual coil system with 3.7 meter coil separation provides 6m penetration.

Pros: reasonable soil penetration depth, possible plastic mine applications

Cons: horizontal range is limited, natural variation in soil conductivity in search area must be accounted for by recalibration. Image resolution is poor, targeting individual mines is not feasible. Capability rests more practically in establishing minefield boundaries. [TR-311]

VI. Mechanical

1. Tactile

Theory- The movement of a tactile sensor arm along the surface of man-made surfaces has been found to produce vibration patterns which reflect distinct resonant frequencies which vary from those produced by natural surfaces such as stone, wood, etc. By using a tactile probe connected to a piezoelectric device, vibrations produced by movement along a surface can be analyzed using Fast Fourier transforms to determine whether frequency patterns indicate possible man-made targets which may be munitions. This system can only be used on munitions which are not buried. It has no ability to discriminate between ordnance and non-ordnance targets, only providing information on whtether the object is man-made. Best incorporated into a sensor suite for use in robotic search/detection systems. [Mangolds, 1993]

Pros: Capable of detecting plastic or metal mines, simple and robust technology, easily adaptable to remote/autonomous operation.

Cons: Inability to discriminate effectively between ordnance and non-ordnance man-made targets.

VII. Optical

Theory- There are two basic categories within this sensor type: passive or active. The first utilizes naturally occurring optical wavelength energies, which it collects and processes to provide required sensor information. The second type system emits energy within these wavelengths and then processes the return signal to provide information.

1. Infrared -A passive system which collects information about the specific infrared spectrum which is emmitted by a surface. It passivley scans large areas in order to determine if variations in emmissivity/soil temperature are present and, additionally if regular, characteristic minefield patterns are present. It has been found that following the emplacement of landmines the disturbed soil will exhibit a different moisture content than nearby undisturbed soils. This moisture differential will lead to a varying infrared signature, which is particularly evident during times of large air/soil temperature differential (evening/morning.) [Keeler, 1995]

Pros: System is particularly well-suited to large scale survey by airborne platforms and incorporation with intelligent microprocessor programs that excel at discerning mining patterns.

Cons: System useful primarily for landmines, rather than individual or random detection. Limited by weather conditions and moisture content of soil.

2. Laser -Laser is a form of highly concentrated light which can be directed onto a surface at known geometries. Its reflection produces information concerning range, phase, and surface type. Laser use has been limted mainly to use in underwater systems such as Magic Lantern and LiDaR, although its application to airborne surface detection appears feasible.[Keeler 1995]

Pros: large area search potential

Cons: limited to surface ordnance, cannot penetrate soil to significant depth.

VIII. Acoustic

1. Ultrasound

Theory- Apply the technology which has already been developed for use in medical diagnosis to ordnance detection.. By directing high frequency acoustic energy from a transducer and measuring reflected energies an image can be produced.

Pros: Excellent resolution

Cons: Very short range due to high frequency attenuation in soils. [TR-311]

2. Seismic

Theory. By directing low frequency acoustic energy into the soil and then using a variety of arrays to detect reflected energies and variation in acoustic wave speed/direction it is possible to resolve buried structures. Paleontologists have been using variations of this technology in researching buried fossils for some years. The feasibility of making the technology portable, in order to cover larger areas of terrain are being pursued by Army researchers. Application involves a truck mounted device using a water column to produce the acoustic energy and towed receiver array.

Pros: Good range and penetration through dense, moist soils, non-magnetic capabilities.

Cons: Large, slow and low frequencies result in poor resolution. [TR-311]

IX. Chemical

These sensors use the chemical properties of the explosives found in ordnance to determine their presense.

1. Vapor Detection-

Theory- The presence, in almost all explosives, of some nitrate form, can be used as a key to determine ordnance presence. Assuming the presence of explosive contamination on the ordnance surface, or lack of hermetical seal to the ordnance case, it is possible to produce a sample of gas found in the buried ordnance airspace and heat the nitrate compounds found therein in the presence of a catalyst to produce nitrous oxide. This gas can then be measured and a direct correlation made to explosive presence. Another variation of this technique requires mixture of nitrous oxide with ozone and measure resulting chemoluminescence using photodetectors. [Patel 1995]

pros: applicable to almost all ordnance types, detects non-metallic ordnance.

cons: current technology required physical application of solvent to ordnance case, resulting in slow, dangerous process.

2. Bioluminescence

Theory- A bacteria which grows exclusively on the explosive known as trinitrotoluene (TNT) has been found. Because TNT is the basis for many common explosive mixtures, the use of this bacteria as an indicator has been researched. One specific enzyme produced by the bacteria, TNT reductase is combined with luciferase (a light emitting enzyme) and NADH to produce a light emmitting substance whose luminescence can be measured to determine explosive presence. The technique is still experimental. No sampling method has been devised. [Patel, 1995]

Sensitivity: Detection of 2X10^-14 molar solution of TNT achieved.

Pros: Applicable to any TNT based explosive, irrespective of mine case.

Cons: Slow, no adequate sample collection method

X. Definitions of Sensor Performance.

In order to quantify and compare the performance of sensors it is important to establish criteria which identifies the ability of the sensor to correctly perform its task. The ultimate sensor will be able to detect ordnance items, provide data on their exact location, while consistently rejecting other detected items that are not ordnance.

In a realistic sensor evaluation, such as the one carried out recently at Jefferson Proving Grounds, Indiana , an effort was made to statistically determine the efficacy of approximately 29 sensor systems. The first step of the evaluation involved establishing a baseline database for the search area where the evaluation was to be conducted. This database included the position and classification of every ordnance and non-ordnance object within the test area.

Each system demonstrator was required to search the area and then provide results which delineated the position of all objects found, and their classification as ordnance or non-ordnance.

Based upon an arbitrary critical radius of detection (rcrit), the two databases could be compared to provide the following information:

- Detected target set (E): Those targets for which the demonstrator declared positions were within the distance rcrit of their baseline positions.

-True Positive set (TP): the subset of the detected targets which were declared to be ordnance and, in fact, were.

-Mistyped Target set (MT): The subset of detected targets which were declared to be non-ordnance but were actually ordnance.

-True Negative set (TN): The subset of detected targets which were declared to be non-ordnance and, in fact, were.

-False Positive set (FP): The subset of detected targets which were declared to be ordnance, but were actually non-ordnance.

-False Negative set (FN): Those items which were detected and declared as ordnance, whose position did not correlate to any baseline objects.

-Negative False set (NF): Those items which were detected and declared as non-ordnance, but whose position did not correlate to any baseline object.

Undetected Ordnance set (UO): Those ordnance objects which were in the baseline database which were not detected by the system.

Undetected Non-ordnance set (UN): Those non-ordnance items which were in the baseline database which were not detected by the system.

This data could be used, in conjunction with known search area size (Area), number of total items placed (B), number of ordnance items placed (BO), number of non-ordnance items placed (BN), and time required for search, to establish a variety of significant parameters for each system's sensor performance.

The performance criteria selected included:

1. Detection Capability-four ratios which provide:

a. overall detection ratio- E/B, the overall ability to find all items. Large number desired.

b. ordnance detection ratio- (TP+MT)/BO, the ability to detect ordnance items, regardless of classification applied.

c. non-ordnance detection ratio- (TN+FP)/BN, the ability to detect non-ordnance items, without regards to misclassified items. (questionable value)

d. mistyped ordnance ratio- (MT)/(MT+TP), the ability to distinguish ordnance from non-ordnance. Low number desired (zero)

2. False Negative Rate-two ratios which provide:

a. false negative ratio- (FN)/(FN+TP), the ability to distinguish ordnance from false returns and clutter. Low score is good.

b. area false alarm ratio-(FN+NF)/area, a measure of false alarms (ie. no item of any type located at position.) A low number is good.

3. False Positive Rate-FP/(FP+TN), one ratio which measures the ability to classify detected items correctly.

4. Target Classification Capability- # of ordnance type detected and correctly classified/ number of ordnance type in baseline database. Example: number of projectiles detected, and correctly classified as such, divided by total number of projectiles present in the baseline database.

XI. Survey of Commercial Sensor Systems

Note: where available some indication of sensor performance in evaluation at Jefferson Proving Ground will be noted. Common performance characteristics which were determined at this 40 acre, mixed munition (bombs, projectiles, landmines, cluster munitions) will include:

Ordnance Detection Ratio (ODR)- the ratio of all ordnance items detected, even if misclassified over the number in a test field.

False Alarm Rate (FAR) - number of items detected which did not actually exist per unit area.

Manufacturer: Lawrence Livermore Laboratories

Sensor Type: GPR/ pulsed side-looking

Sensor characteristics: 400Mhz-1500Mhz, 3kv pulse

Platform: vehicle or airborne

Swath/depth/clearance rate: 10m./-/ Clearance rate dependent upon platform

Primary munition type/material/size detected: antitank mines, bombs/metallic/>30 cm

Sensor limitations: soil dielectric, moisture content affects performance.

Contact/Non-contact

Pros: 9 meter standoff, relatively fast clearance rates

Cons: Large power and data processing requirements. Soil characteristics must be matched for best performance.

Comments: GPR performance is heavily dependent upon soil types. [Sargis, 1995]

Manufacturer: Lawrence Livermore Laboratories

Sensor Type: Micropower Impulse radar

Sensor Characteristics: ultra-wide bandwidth,

Platform: Vehicle

Swath/depth/clearance rate: 2m^2 per /2-10 cm/-/

Primary munition type/material/size detected: antitank mines/metal or plastic/-/

Sensor limitations: high frequency band loss in some soils.

Contact/Non-contact

Pros: lower cost,power and weight than GPR. detects non-metallic objects.

Cons: Small stand-off for detection

Comments: Produces two or three-D tomographic images. Not ready for fielding just yet. [Gavel, 1995]

Manufacturer: SRI

Sensor Type: GPR

Sensor characteristics: Synthetic aperture, pulsed radar

Platform: plane w/DGPS link

Swath/depth/clearance rate: /-/5ft/50sq kn per hr/

Primary munition type/material/size detected: bomb/metallic/large

Sensor limitations: GPR soil dependency, platform can only operate in fair weather to allow for smooth transit at low altitude.

ODR: .011

FAR: 1.95

Pros: fast clearance rates

Cons: In actual testing performance was very poor.

Comments: GPS adaptation to airborne platform not yet feasible. [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Geonex Aerodat

Model: Scintrex

Sensor Type: Cesium vapor optically pumped magnetometers

Sensor characteristics: Two cesium vapor magnetometers mounted at opposite ends of a 6-m kevlar tube towed beneath a helicopter.

Platform: helicopter w/DGPS link

Swath/depth/clearance rate: /-/5ft/50sq km per hr/

Primary munition type/material/size detected: bomb/metallic/large

Sensor limitations: Towed body affected by wind. Poor ability to correlate target detect to positional accuracy due to platform/ground dynamics.

ODR: .04

FAR: .95

Pros: fast clearance rates

Cons: In actual testing performance was very poor, with overall detection ratios less than 5 per cent. [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Foerster

Sensor Type:Magnetometer- Ferex MK 26

Sensor characteristics: N/A

Platform: man carried

Swath/depth/clearance rate: -/2-5 ft/4 acres per day

Primary munition type/material/size detected: Bombs/metals

Sensor limitations: metals only

ODR: .38

FAR: 3.2

Pros: small, rugged, lightweight, low power

Cons: relatively slow clearance rates, no classification ability, ineffective with plastic.

Comments: Currently one of Navy EOD tool sets [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Geometrics

Model- MagDis (prototype)

Sensor Type: Optically pumped cesium magnetometer

Sensor characteristics: 5 cesium magnetometer sensors mounted in array

Platform: man portable (towed)

Swath/depth/clearance rate: 10ft/ >6 ft/7 acres per day

Primary munition type/material/size detected: mortars and bombs/iron

Sensor limitations: iron only

ODR: .22

FAR: .43

Pros: classification capability

Cons: no plastic capability

Comments: Best performance for large deep targets. Processing accomplished via tether to trailing trailing ATV data processing module.[Institute for Defense Analysis ,Mar 1995]

Manufacturer: Georadar

Model: Georadar 1000A

Sensor Type: GPR

Sensor characteristics: stepped frequency modulated signal

Platform: manportable (towed two-wheeled array)

Swath/depth/clearance rate: -/5-10 ft/ .5 acre per day

Primary munition type/material/size detected: projectiles/metal

Sensor limitations: no classification capability

ODR: .05

FAR: .13

Pros: may work on plastic mines.

Cons: Difficulty in heavy wet clay soils, very slow.

Comments: preproduction model used in testing, poor performer. [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Australian Defense Industries

Model: GT-TM4

Sensor Type: optically pumped magnetometer

Sensor characteristics: N/A.

Platform: Man portable or towed

Swath/depth/clearance rate: 10/20 acres per day depending on platform

Primary munition type/material/size detected: bombs, mortars and projectiles/ferrous

Sensor limitations: ferrous metals only

ODR: .40

FAR: .43

Pros: good performance on large ferrous objects

Cons: no classification ability, ferrous only

Comments: During testing all metal objects with a mass of 100 gr or more were declared as ordnance. Man-portable operation requires two men. [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Chemrad

Model: 8221

Sensor Type: Optically pumped magnetometer

Sensor characteristics: N/A

Platform: man portable or surface towed

Swath/depth/clearance rate: 20 ft/-/10 acres per day

Primary munition type/material/size detected: bombs/ferrous

Sensor limitations: No plastic capability

ODR: .26

FAR: 1.9

Pros: fair performance against large ferrous objects

Cons: No classification ability, poor sensitivity

Comments: none [Institute for Defense Analysis ,Mar 1995]

Manufacturer: Schonstedt

Model: MAC 51-B

Sensor Type: magnetic induction

Sensor characteristics: pulsed 82.5 kHz excitation frequency

Platform: man portable

Swath/depth/clearance rate: N/A

Primary munition type/material/size detected: Designed for pipe/cable detection

Sensor limitations: metallic objects only

Pros: rugged, low power, commercially available

Cons: not designed with ordnance in mind

Comments: no actual data available on performance in ordnance detection

Note: Data derived from manufacturer's information pamphlet

Manufacturer: Schonstedt

Sensor Type: Fluxgate magnetometer

Sensor characteristics: N/A

Platform: man-portable

Swath/depth/clearance rate: N/A

Primary munition type/material/size detected: bombs and projectiles/ferrous

Sensor limitations: detects only ferrous metals

ODR: N/A

FAR: N/A

Pros: small, lightweight, rugged, typical fluxgate magnetometer

Cons: lack of sensitivity, detects only ferrous metals

Comments: all-purpose magnetometer which can also be used for ordnance.

Note: Data derived form manufacturer's information pamphlet

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DOCUMENT 2

Unexploded Ordnance: A Coordinated Approach to Detection and Clearance is Needed

ADA 300773

September 1995

General Accounting Office, Washington, DC
National Security and International Affairs Division

United States General Accounting Office

GAO

Report to Congressional Requesters

September 1995

UNEXPLODED ORDNANCE

A Coordinated Approach to Detection and Clearance Is Needed

GAO

United States
General Accounting Office
Washington, D.C. 20548

National Security and
International Affairs Division

B-258886

September 20, 1995

The Honorable Floyd D. Spence
Chairman
The Honorable Ronald V. Dellums
Ranking Minority Member
Committee on National Security
House of Representatives

Over the past 2 years, several accounts of the casualties caused by antipersonnel landmines have brought to light the threat such munitions pose years after hostilities cease. The deaths and injuries attributed to these mines each year have been estimated to total about 30,000. Many of the victims are civilians, including children. While the contamination of land caused by landmines and other forms of unexploded ordnance (UXO) may appear to be primarily a Third World issue, closer examination suggests that the problem is shared by developed nations as well.

As you requested, we assessed the extent to which ongoing or foreseeable technology efforts offer solutions to worldwide landmine and other UXO problems. More specifically, we

- reviewed the extent to which the Department of Defense's (DOD) and other agencies' requirements and associated research and development may have application to clearance problems elsewhere in the world,
- assessed the ability of existing or foreseeable technologies to detect and clear landmines and other UXO, and
- identified barriers that could impede the progress or output of such technology.

Background

DOD defines "explosive ordnance" as all munitions, weapon delivery systems, and ordnance items that contain explosives, propellants, nuclear materials, and chemical agents. Included in this definition are bombs, missiles, rockets, artillery rounds, ammunition, mines, and any other similar item that can cause injury to personnel or damage to material. UXO consists of these same items after they (1) are armed or otherwise prepared for action; (2) are launched, placed, fired, or released in a way that they cause hazards; and (3) remain unexploded either through malfunction or design.

Antipersonnel mines pose a particularly difficult clearance problem because they are hard to detect, inexpensive, and prone to proliferation. The Department of State considers landmines to be a distinct class of weapon that is subject to specific doctrinal and international legal controls. Landmines—particularly antipersonnel mines—may pose a greater hazard to innocent civilians than items such as unexploded bombs because they are intended to detonate when a person steps on or near them. Landmines are considered to be a valuable military asset since, by slowing and possibly demoralizing opponents, they multiply the combat impact of defending forces. Their attractiveness to smaller military and paramilitary organizations, such as in the Third World, is further enhanced because mines do not require complex logistics support and are readily available and inexpensive—some can be bought for as little as $3 each.

Over 60 countries, developed and undeveloped, report a need to clear areas from landmine and other UXO contamination. As of December 1994, the Department of State estimated that 80 million to 110 million landmines remain uncleared worldwide, the bulk of which are in undeveloped countries. Most of these countries' economies depend heavily on agriculture and thus are particularly vulnerable because the presence of landmines can deny farmers large sections of land. Within the United States, DOD estimates that over 900 military sites are contaminated with UXO. DOD estimates that it has already cost $10.3 billion through fiscal year 1994 to clean up sites contaminated with hazardous materials, including UXO, and that it will cost an additional $31 billion for future actions. In European countries, millions of bombs, landmines, and other munitions from World Wars I and II still remain uncleared.

Results in Brief

U.S. research and development requirements for UXO detection and clearance technology are broader today than they were during the Cold War years and thus have more in common with the worldwide problem. Traditionally, DOD's technical efforts have supported countermine operations, for which the main priority is rapidly "breaching" or making paths through minefields during combat. "Clearance" differs from breaching because it requires that large areas—such as farmland—be cleared and timeliness is not as critical. With the dissolution of the Soviet Union, U.S. requirements have evolved that have more in common with area clearance than breaching. These other requirements include clearing (1) U.S. military sites of UXO and other hazards and (2) areas and roads needed for conducting operations other than war, such as peacekeeping. Such broader requirements make it likely that research and development sponsored by DOD will have more direct application to the clearance problems faced by Third World countries. Other agencies, such as the Departments of Energy, Transportation, and Justice also sponsor research and development applicable to the detection and clearance of explosives and other hazards.

U.S. research and development efforts cover a group of technologies that can be categorized as (1) near-term, less advanced technologies that can be put to work immediately and (2) advanced technologies that will take time to develop but could greatly speed up the detection and clearance functions. However, the technologies available today to clear wide areas are inadequate and cannot keep pace with the number of landmines being emplaced annually. For example, the United Nations estimated that in 1993, 2.5 million mines were emplaced, while only 80,000 were removed. The most effective techniques, such as hand-held probes and metal detectors, are time-consuming, expensive, and labor-intensive. While heavy mine clearing equipment, such as plows, is suited to breaching paths, it is not practical for clearing large areas. Also, current technologies do not perform well against newer, more advanced munitions. For example, metal detectors are ineffective against newer antipersonnel mines that contain little or no metal. Moreover, recent technology demonstrations showed the more advanced methods to be much less reliable than traditional methods.

Several factors limit the potential output from the U.S. investment in technologies related to the detection and clearance of landmines and other forms of UXO. Although numerous U.S. organizations within and outside DOD are sponsoring technologies that could have application to the problem, no overarching, governmentwide strategy or organization exists to ensure that the most is gained from these various efforts. Moreover, it is difficult to develop an accurate estimate of how much funding these organizations are collectively providing for applicable technologies or whether that level of investment is sufficient. The House Committee on National Security recently took a step to address this problem by directing the Secretary of Defense to develop a plan to improve the management and cooperation of technology efforts directed at landmine and other UXO clearance.[1] Other barriers to technical solutions include the relative ease with which inexpensive improvements in mine designs have outstripped detection and clearance methods, the unique area clearance challenges Third World countries pose, and the difficulty of controlling the proliferation of antipersonnel landmines.

[1]National Defense Authorization Act for Fiscal Year 1996, H.R. Rep. 104-131, p. 95.

Emerging U.S. Requirements May Spawn Technology That Is More Applicable to Worldwide Problems

Comparison of Combat and Noncombat Clearance Requirements

A primary focus of DOD's research and development activities in detection and clearance has been on the countermine mission in support of combat operations. In combat, mines are seen as an obstacle in the way of an attack or a maneuver; overcoming these obstacles involves rapidly detecting, breaching, and marking paths while under assumed enemy fire. Some casualties are expected and accepted. Most of these countermine operations are destructive because heavy or destructive equipment such as plows, rollers, flails,[2] and explosives—are used to breach enemy minefields. Once breached, the cleared paths are marked so that following forces can traverse the minefield safely. These operations do not require the identification of the exact locations of the mines. Also, the operations do not require that an entire area be cleared unless the area is to be occupied for future operations.

Detecting and clearing landmines and other UXO in noncombat situations in some ways is less demanding and in other ways more demanding than countermine operations. In noncombat situations, neither time nor enemy fire is a constraining factor, so detection and clearance operations take place under much less hostile circumstances. On the other hand, because the noncombat objective is to render an area safe and worthwhile to repopulate, the corresponding objective is to detect and clear all landmines and other UXO. Thus, not only must contaminated areas be positively identified to very high standards of reliability, but efforts must be made to find all munitions and other hazards. Once found, the explosives must be removed or neutralized in an environmentally sound way. In the process, care must be taken not to destroy the land or infrastructure.

These differing demands produce corresponding differences in research and development priorities. For example, money spent to develop an

[2]Flails generally consist of hardened cylinders with heavy chains that pummel the ground by spinning. They are mounted on heavy vehicles.

improved plow for an M-1 tank may be a good investment for the countermine mission, but it is not necessarily practical for noncombat operations. Similarly, a detection technology that takes a lot of time may work well in a noncombat situation, but be too slow for countermine operations. On the other hand, countermine and noncombat missions do share some requirements and benefit from the attendant technologies. If a military force plans to occupy a mined area, it must use detection and clearance technologies and methods aimed at achieving as near as possible a 100-percent clearance.[3] Also, it is beneficial to combat forces to detect the presence of minefields so that they can be avoided, if possible. Such a detection capability would also benefit noncombat clearance operations, even if the exact locations of individual munitions could not be pinpointed, because unsafe areas could be posted or cordoned off and avoided by civilians.

Broader U.S. Area Clearance Requirements Have Emerged

Several factors have converged into a set of emerging U.S. requirements that go beyond the countermine mission and address the need for detecting and clearing all hazards, including landmines and other UXO. Following the dissolution of the Soviet Union, the United States has become more involved with operations other than war, including special operations, low-intensity conflicts, and peacekeeping. These operations require U.S. and other forces to routinely clear operational areas and infrastructure—such as roads and buildings—of mines and other explosives. In addition to open area clearance, DOD has developed urban warfare requirements that include the detection and clearance of mines and booby traps. It should be noted that while U.S. military personnel will perform such operations when U.S. interests are at stake, it is against U.S. policy for them to physically remove landmines from other countries for humanitarian purposes.

In addition, the closing of numerous bases per the recommendations of the base realignment and closure process and the environmental cleanup of other defense sites have generated a sizeable clearance requirement. Many of these sites, such as test ranges, impact ranges, and training sites, contain large areas of UXO contamination. Clearing these areas—even partially—so that they can be used for other purposes requires detection and clearance methods to meet a 100-percent clearance objective. The research and development efforts sponsored by DOD to support operations such as peacekeeping and base cleanup are likely to have more direct

[3]DOD's specific requirement is 99.9-percent clearance at a depth of 18 inches.

application to the clearance problems faced by Third World countries than those efforts supporting countermine operations.

Other U.S. agencies besides DOD are responsible for detecting and clearing explosives and other hazards. For example, the Departments of Treasury, Justice, and Transportation conduct or sponsor research and development of technologies to help curb terrorism, such as detecting explosives and weapons in airports, aircraft, and public buildings. The Department of Transportation is also responsible for detecting subsurface flaws in roads and bridges. The Department of Energy and the Environmental Protection Agency are responsible for detecting hazardous materials, such as buried radioactive and chemical waste. These research and development efforts have some commonality with those needed to detect and clear landmines and other UXO. Specifically, they involve (1) detecting the presence and exact location of explosive and hazardous materials in the open, underground, or hidden in a building or vehicle; (2) removing or neutralizing the materials; and (3) using methods that allow maximum standoff distances.

European countries have had broad clearance requirements for a long time as they are still clearing areas from World Wars I and II. For example, in Verdun, France, millions of UXO items from World War I still have not been found or cleared. Germany has been clearing UXO from Berlin since World War II ended. The United Kingdom has clearance requirements both at home following World War II bombardments and abroad. For example, after the Falkland Islands war, the United Kingdom sponsored efforts to detect and clear remaining mines there.

An Ideal Solution Is Not Foreseeable Based on Known Technologies

Current Technology

Currently, hand-held probes, metal detectors, trained dogs, and mechanical breaching equipment are considered the most effective tools to detect and/or clear landmines and other UXO. These methods are slow, costly, and labor-intensive. They mainly find landmines at or near the surface, although some metal detectors can find larger, more deeply buried UXO items because of their greater metal content. Although current methods offer the greatest assurance that an area is safe to use, they are also quite dangerous because they put the operator in close proximity to the explosive. For example, in the post-Gulf War cleanup of Kuwait, 84 operators, including at least 2 private U.S. contractors, were killed using these methods. This number of fatalities is more significant when one considers that the mines in Kuwait were easier to find than in some Third World countries because they were in sand and had been placed in patterns according to known military doctrine.

Metal detectors have been in use since World War II and are still the most effective sensors for use against landmines and other UXO. There are two types of metal detectors. One detects anomalies in the earth's magnetic field caused by ferrous (iron-based) materials. The other creates an electromagnetic field that can detect both ferrous and non-ferrous metals. Improvements made to metal detectors have reportedly been in processing sensor information, weight reduction, and improved sensitivity to disturbances in the magnetic field caused by metallic objects. Detection of trace metal elements and debris—found in most soils—still leads to a high level of false alarms since operators are often unable to discriminate between a metal fragment and a mine. False alarms translate into increased workload because each detection must be treated as if it were an explosive. Efforts to duplicate the knowledge, skills, and abilities of a proficient operator through computers and artificial intelligence have not yet proven successful.

Trained dogs have proven effective at detecting hidden explosives. South Africa has developed a system that uses blast-hardened vehicles to collect air samples from geographical sectors in filter canisters. The dogs can then detect which canister—and thus which sector—contains any evidence of explosives. These sectors can then be cleared using traditional methods. Since dogs have been extremely efficient in pinpointing the location of landmines, research and development efforts have been underway to duplicate the dogs' abilities through development of artificial biosensors, spectrum analysis, and computer intelligence. However, no sensor technology has been developed that can replicate the dogs' ability to sense explosives.

Mechanical equipment used in combat operations to clear mines includes armored vehicles equipped with devices such as plows, flails, and rollers. This equipment clears a path by pushing mines aside or detonating them. It is not effective in rough or rocky terrain and against more advanced, off-route or wide-area mines. However, these advanced mines do not yet make up a large portion of the landmines already emplaced in Third World countries. For these reasons, and because of the potential environmental impact, such as pollution and soil erosion, heavy mechanical equipment is of limited use for wide-area clearance. Another technique used in combat is the explosive line charge. The line charge is a cord or rope of explosives that is fired across a suspected minefield. The explosives are set off to detonate or disable nearby mines and thus clear a path. Line charges have been used since World War II and are still being improved today.

All of these methods are slow and costly. For example, the Navy estimates that it would take $2 billion and 20 years to clear the 28,800-acre Hawaiian island of Kaho'olawe to achieve a 4-foot depth needed for farming. The services have used the island as a bombing range since 1941. Similarly, we have previously reported that a study of the Jefferson Proving Ground found that current cleanup technologies were not practical for removing the UXO from the installation's 51,000 heavily forested acres.[4] Army officials estimated that cleanup estimates for the installation could range from $5 billion to $8 billion. These estimates underscore the current challenge the United States faces in cleaning up millions of acres of its defense sites. The worldwide challenge is even more daunting.

Advanced Technology

Generally, more advanced technologies being pursued aim to make the detection of landmines and other UXO quicker, safer, and more cost-effective. They employ sensors that can be operated from remote distances, such as from manned or unmanned ground and air vehicles. However, no revolutionary area clearance technology with acceptable reliability has been forthcoming. Most of the advanced technologies have drawbacks such as weaknesses under certain environmental conditions or impractical power requirements. At this point, the more promising efforts involve using a combination of technologies either concurrently or sequentially. While standoff sensors do not perform as well as current hand-held methods, they can perform initial searches for landmines and other UXO to help identify contaminated areas that are ultimately cleared using traditional methods.

Advanced sensor technologies with application to detection and clearance can be grouped as follows: infrared sensors, ground-penetrating radars, microwave, photon backscatter, nuclear or thermal neutron analysis, and lasers. Their characteristics are summarized in table 1.

[4]Military Bases: Environmental Impact at Closing Installations (GAO/NSIAD-95-70, Feb. 23, 1995).

Table 1: Advanced Detection and Clearance Technologies

Technology	Characteristics	Comments
Infrared sensor	Looks for differences in surface radiation caused by objects or disturbances in the soil. Affected by ambient temperatures, high levels of soil moisture, and vegetation density.	Only effective against UXO at or near the surface and against UXO that has not been in the ground too long.
Ground-penetrating radar	Emits short pulses of electromagnetic energy of various wave lengths (including microwave) into the ground. Returning signals are collected by arrays of detectors.	Effectiveness varies with changes in atmospheric conditions. Ineffective in moist soils without a high-power system; cost-effective means of meeting these power requirements in the field is lacking. Trade-offs exist between radar wave length, depth of ground penetration, and resolution.
Microwave	In addition to its application to ground-penetrating radar, a high-powered microwave system could be used to neutralize UXO in situ.	Large power needs. Can affect soil characteristics and harm life forms and equipment.
Photon backscatter	Scans the ground with a pencil-thin beam of X-rays. X-rays produce scattered returns from objects that are collected by detectors on either side of the vehicle and processed.	Early in development. Has large power needs, slow speed, and a small footprint. Can change soil characteristics and harm life forms and equipment. Has a high data processing requirement.
Nuclear or thermal neutron analysis	One application uses californium (a radioactive element) to excite explosive material to release gamma rays that can be detected. Another application excites hydrogen in an explosive that releases neutrons that can be detected.	Early in development. Has a small footprint. Hydrogen sensors are not effective in moist soil.
Laser	Irradiates small areas of ground so mines and other UXO at or near the surface may react to this type of laser energy by emitting heat and light, unlike the surrounding soil. Other sensors, such as infrared and hyperspectral, may be used to detect the reactions and pinpoint the UXO. Also being developed to neutralize and to help map locations.	Neutralization and irradiation types have high power requirements. Can affect soil characteristics and harm life forms and equipment. Hyperspectral sensor's large data processing requirements tax the capacity of airborne platforms.

Some promising recent research and development efforts involve coupling sensor technologies. For example, the Army has the Airborne Standoff Minefield Detection System under development that combines infrared and laser sensors. The Marine Corps has a project underway that couples ground-penetrating radar and infrared sensors. The Department of Energy has initiated a subsurface imaging program utilizing ground-penetrating radar and seismic measurements. Several projects are also underway that link sensors with the satellite-based Differential Global Positioning System. Linkage to this system can help map geographical locations of landmines and other UXO.

Advances in mine technologies have been made that can reduce the amount of contamination posed by landmines and other UXO in the future. Specifically, DOD has developed self-destruct mechanisms that detonate munitions a specified time after they have been deployed. According to DOD officials, such mechanisms have been incorporated into U.S. landmines since 1979. While not foolproof—self-destruct mechanisms have demonstrated 90 percent reliability in testing—they do reduce the risk of injury to innocent civilians. DOD officials noted that not all U.S. landmines contain self-destruct mechanisms because some minefields are intended to stay active indefinitely. Self-destruct mechanisms are currently being developed for submunitions, but are not yet fielded. DOD is also developing mechanisms that can detonate munitions on demand from remote locations.

Technology Demonstrations Have Not Identified an Ideal Solution

Although numerous efforts to advance technology have been made, demonstrations have not produced an ideal solution. The Army Environmental Center, in cooperation with Naval Explosive Ordnance Disposal Technology Division,[5] has been conducting an Advanced Technology Demonstration for the detection, identification, and clearance of UXO, including landmines. The demonstration was mandated by the Congress in fiscal years 1993 and 1994. The purpose of this effort was to demonstrate the best available off-the-shelf detection and clearance technologies. Thirty-three projects were demonstrated, with most coming from private industry and a few from government laboratories. The demonstration projects represented airborne, ground vehicle, and man-portable platforms with metal detectors, ground-penetrating radar, and infrared sensors. The test areas included a variety of ordnance buried at realistic depths; however, the terrain was relatively benign—open, clear, and level. Target processing software and clearance technologies were also demonstrated. Some used multiple sensors, such as ground-penetrating radar with infrared or metal detectors.

The goals of the demonstrations were to (1) survey large areas; (2) determine density of UXO, as well as type, depth, and exact location; (3) discriminate between UXO and other objects; and (4) demonstrate UXO detection, identification, and clearance systems as integrated technology. UXO, scrap metal, and other objects were planted in two courses—one for ground systems and one for airborne systems.

Demonstration results showed that none of the technologies, either individually or coupled, came close to approaching 100-percent clearance. UXO detection ranged from 0 to 59 percent, with the ground-based systems

[5]Although this organization originated under the Navy, it is jointly staffed and funded to conduct UXO research, development, and operations for all three services.

performing the best, especially when vehicle-mounted and man-portable systems were used together. However, the ability to separate UXO from false alarms was dismal for all technologies demonstrated. Again, the ground-based systems were the most reliable, but the system with the highest detection rates did not finish the course in the required time. All but one airborne system completed the course in the required time, but the airborne systems were the least effective of all systems. The clearance systems in the demonstration, which relied on robotics excavations, were considered effective but time-consuming.

Several Factors Could Impede the Progress of Future Efforts

Many Organizations Are Involved With Detection and Clearance Technologies, Operations, and Policies

We identified over 20 U.S. organizations that directly or indirectly conduct or sponsor research and development with application to detection and clearance, review related programs and policies, conduct detection and clearance operations, or provide funds or related training. Some of these organizations are shown in table 2.

Table 2: U.S. Organizations Involved in Detection and Clearance Technologies

Organizations	Conducts or sponsors research and development	Reviews research and development policies or programs	Conducts or sponsors detection and clearance operations and/or training
Office of the Secretary of Defense, Defense Acquisition and Technology	X	X	X
Office of the Joint Chiefs of Staff	X	X	
Office of the Secretary of Defense, Special Operations and Low-Intensity Conflict	X	X	X
Advanced Research Projects Agency	X	X	
Army Environmental Center	X	X	X
Program Executive Officer for Armored Systems Modernization, U.S. Army	X	X	X
Army Communications Electronics Command, Mine, Countermine, and Demolitions	X	X	X
Army National Ground Intelligence Center		X	
Air Force Materiel Command	X	X	X
Naval Explosive Ordnance Disposal Technology Division	X	X	X
Office of Naval Research	X	X	
Marine Corps Amphibious Warfare Technology	X	X	X
Marine Corps Intelligence Activity		X	
Department of Energy, Environmental Restoration and Waste Management, Technology Development	X	X	X
Environmental Protection Agency	X	X	X
Department of Justice, Federal Bureau of Investigation	X	X	X
Department of Transportation, Federal Aviation Administration	X	X	X
Department of State, Bureau of Political-Military Affairs		X	X
U.S. Agency for International Development			X
Interagency Working Group on Demining and Landmine Control		X	X
Department of Treasury, Bureau of Alcohol, Tobacco, and Firearms	X	X	X

The number of U.S. organizations involved is greater than indicated in the table because the different offices in the service commands are involved with one or more forms of UXO, national laboratories conduct research and development for DOD, and individual contractors work for different agencies or on commercial applications. Organizations outside the United States are also involved with detection and clearance technologies. For example, the United Nations is actively involved with clearing landmines from Third World countries and promoting policies to counter proliferation. Many individual countries have been working on countermine operations and UXO clearance and are developing clearance technologies and methods. These countries include the United Kingdom, France, Sweden, Germany, Russia, and South Africa.

Research and Development Efforts Are Not Well-Coordinated

No formal mechanism or strategic plan exists to ensure that a fully coordinated U.S. research and development effort is leveraged at the problem. This situation exists because the organizations involved with technologies related to detection and clearance are seeking solutions to more narrowly defined problems that fall under their purview. For example, the combat branches of the military services have traditionally pursued solutions to the countermine problem. The Department of Energy and the Environmental Protection Agency sponsor research and development to detect and clear hazards such as subsurface radioactive, chemical, and other waste. The Federal Aviation Administration and the Federal Bureau of Investigation sponsor research and development to see through concealments to detect explosives, firearms, and contraband. More recently, DOD has sponsored technology efforts to facilitate cleanup of defense sites.

Nonetheless, when requirements are more broadly defined as the detection and clearance of harmful, hidden objects or voids (such as concrete flaws and underground facilities), the technologies that various agencies employ or are developing for their own missions can be related. For example, the Army, the Navy, and the Department of Energy are either sponsoring research and development in or have experimented with ground-penetrating radars. This does not necessarily mean that unwanted duplication is occurring, but it does illustrate the potential for one agency to be aware of and possibly take advantage of relevant technologies other agencies are working on.

Some interagency coordination occurs on an ad hoc or narrow basis, such as through symposia, technology demonstrations, and joint programs, but this does not necessarily provide a firm basis for technology exchange. Most of the participants at an interagency UXO forum that we sponsored in May 1995 cited the lack of a coordination mechanism as a barrier to making progress in technologies applicable to the detection and clearance of landmines and other UXO. They also pointed out the need for an overarching research and development plan for these technologies and for an entity to be charged with overseeing and coordinating the relevant technology efforts.

Even within DOD, full coordination between agencies working on detection and clearance technologies is not occurring. In particular, agencies that are responsible for cleaning up military sites and those responsible for countermine missions are not always working together, even though they share interests in many of the same technologies. Currently, two demonstrations of detection technologies for use against landmines and other forms of UXO are underway. One is being conducted by the Army Communications Electronics Command, which sponsors countermine research and development, and the other is being jointly conducted by the Army Environmental Center and the Naval Explosive Ordnance Disposal Technology Division. Neither organization has participated in the other's demonstration. Perhaps illustrative of the need for broader coordination is the fact that several similar demonstrations have been conducted in the past 5 years by the Department of Energy, the Army, and the Marine Corps.

Several cooperative efforts have been undertaken by U.S. organizations. In September 1993, the National Security Council established what became known as the Interagency Working Group on Demining and Landmine Control. The group plans, funds, and organizes operations to remove landmines from Third World countries. It also established a research and development subgroup to promote improvements in area clearance technologies. The group includes representatives from the Departments of Defense and State, the U.S. Agency for International Development, and the Central Intelligence Agency. However, not all U.S. organizations involved in technology applicable to the detection and clearance of landmines and other UXO are represented.

Within DOD, several organizations have begun to develop mechanisms for coordinating, planning, and budgeting countermine research and development activities. While these efforts may improve coordination, they involve agencies within the countermine community. The Navy and the Marine Corps have recently initiated efforts to formally recognize clearance technology as beneficial to their individual missions. The Marine Corps and the Navy have established a Mine Warfare Program Executive Office and a Shallow Water Mine Countermine Steering Committee. The Army and the Marine Corps have established a joint demonstration effort that is directed toward identifying advanced concepts for a potentially integrated countermine capability. The Mine Countermeasures Subpanel under the Joint Directors of Laboratories, established within the last 2 years, is a multiservice mechanism that involves all of the services.

The number of different U.S. organizations supporting relevant research and development also makes it difficult to gauge the level of funding the United States is devoting to technologies that can detect UXO and other hazardous materials. For example, based on fiscal year 1996 budget estimates, the Departments of Defense, Energy, and Transportation could invest somewhere between $75 million and $150 million in research and development efforts that may have some application to the detection and clearance of landmines and other UXO. However, it is unclear how much of that amount is directly related to detection and clearance technologies that have application to noncombat situations. Accordingly, it is difficult to determine whether the United States is getting the most from its level of investment in these technologies or whether the current level matches known national requirements.

Other Impediments to Seeking Technical Solutions

Even if the maximum output could be gained from the various organizations sponsoring research and development, several other factors could blunt the effect of technology gains. One factor is mine technology's ability to stay ahead of detection and clearance technologies. For example, some new mines are made of plastic, composite, and ceramic components, and have little or no metallic content. Thus, the effectiveness of the metal detector, which is one of the most widely used detection technologies, is limited against such mines. Some mines are designed to prevent premature detonation, such as when they are blasted with explosives or dropped. For example, some have air bladders that react to blast or overpressure and inflate to disarm and, then, rearm to await their intended targets. In addition, scatterable mines have been developed that can be deployed by air, increasing the number of these mines that can be rapidly deployed exponentially. Despite these advances, service officials note that even the traditional research and development efforts devoted to the countermine mission have historically been accorded relatively low funding priority.

The characteristics of the country to be cleared can also affect the applicability of a given technology. For example, detection and clearance equipment to be used by Third World countries must be inexpensive to buy and maintain as well as easy to understand and use. From a cost and logistics support perspective, a sophisticated military technology may not be practical in such circumstances. Landmine and other UXO detection and clearance equipment must be effective given the geographical and terrain characteristics at hand. For example, soil with traces of metal elements can confuse metal detectors, and rocky soil impairs hand-held probes. High levels of moisture in soil can affect the performance of detection technologies. Mountainous or forested terrain makes technologies that depend on large or heavy vehicles impractical.

Finally, despite the efforts of the United Nations, the landmine problem continues to worsen. Each year, many more mines are emplaced than can be removed. For example, the United Nations estimated that in 1993, 2.5 million mines were emplaced, while only 80,000 were removed. The primary mechanism for controlling the use of landmines is contained in Protocol II of the 1980 Convention on Conventional Weapons. The protocol was designed to reduce the harm to innocent civilians. It limits the use of landmines and booby traps to military objectives, prohibits their use against civilian populations, requires that parties to a conflict try to ensure that the location of minefields is recorded, and requires that scatterable mines contain self-destruct mechanisms or have their location recorded.

The protocol has been largely ineffective for several reasons. First, it covers only international conflicts, while most landmine-related injuries have resulted from civil or internal conflicts. Second, it does not regulate the production, stockpiling, transfer, or export of landmines. Third, it contains no provision for monitoring compliance, conducting enforcement, or penalizing violators.

The Congress and the Executive Branch Have Taken Actions to Help Resolve the Landmine Problem

The executive branch and the Congress have taken several actions over the past 3 years to curb the proliferation of landmines and improve research and technology directed at detecting and clearing landmines and other UXO. In October 1992, the United States adopted a unilateral export moratorium on antipersonnel landmines, which has been extended until 1996. According to DOD, the United States was the first country to take such a step, which has led other countries to follow suit. In his address to the U. N. General Assembly in 1994, the President called for the eventual elimination of antipersonnel landmines and for the international control of production, export, and stockpiling as the first step toward elimination. On March 24, 1995, the Senate gave its advice and consent and the President ratified the 1980 Convention on Conventional Weapons as well as Protocol II. In addition, the United States was an active participant in the July 1995 International Meeting on Mine Clearance in Geneva, Switzerland.

Beginning on September 25, 1995, 48 nations will convene as full parties to reopen the Convention on Conventional Weapons and conduct a conference to review the Convention, including Protocol II on landmine use. Other signatories and observers are also expected to participate in the conference, which will consider several proposals to strengthen Protocol II. The executive branch strongly supports strengthening the Convention by (1) extending its scope to include internal conflicts, (2) limiting the use of non-self-destructing antipersonnel landmines to marked and monitored areas, (3) making the party that placed the mines responsible for clearing them, (4) banning nondetectable mines, and (5) creating a system to verify the restrictions on mine usage.

In the conference report accompanying the National Defense Authorization Act for Fiscal Year 1994, the Congress directed DOD to undertake a large-scale detection and clearance technology demonstration. Although this demonstration did not produce breakthrough solutions, it did establish a baseline for assessing the state of the art in UXO detection technologies. In the conference report accompanying the National Defense Authorization Act for Fiscal Year 1995, the Congress directed the Army to develop technologies for mine detection and neutralization for use in humanitarian mine removal operations and operations other than war. Such technologies were to be capable of being shared in an international environment. In its report on the fiscal year 1996 DOD authorization bill, the House Committee on National Security cited the need for a central authority to plan, oversee, and coordinate the research, development, and acquisition of the technology applicable to area ordnance clearance. It directed the Secretary of Defense to submit a plan that defines research and development priorities, program management, and cooperative activity with international programs.

Recommendations

The numerous research and development efforts funded by the United States and by other countries could be more productive if they were linked by a common purpose—the detection and clearance of landmines and other UXO. Such a common purpose should complement—not supplant—individual missions, such as countermine, cleanup of hazardous waste, cleanup of bases, and humanitarian demining, by serving as a vehicle for sharing technical progress and avoiding duplication.

Accordingly, we recommend that the Secretary of Defense include in the research and development plan called for by the House Committee on

National Security, a proposal on how a multiagency clearinghouse function could be performed to

- maintain visibility over all federally funded research and development projects with application to detection and clearance of landmines, other UXO, and other hazards;
- develop an overarching strategy that encompasses both near-term and long-term priorities for detection and clearance technologies; and
- serve as an active link to relevant international and private research and development efforts.

Such a proposal should be based on consultation with the Secretary of State, the Secretary of Energy, and the heads of other federal agencies that sponsor research and development that may have application to detection and clearance of landmines, other UXO, and other hazards.

We further recommend that the Secretary of Defense designate an executive agent to serve as a clearinghouse for research and development efforts within DOD that may have application to detection and clearance of landmines, other UXO, and other hazards. The role of such an agent would be to gain visibility over and to leverage these efforts against the broader problems of detection and clearance rather than to champion an individual mission.

Agency Comments

Both DOD and the Department of State concurred with our recommendations. In its comments (see app. I), DOD stated that it could prepare a proposal detailing the functions of a multiagency clearinghouse and that statutory language could facilitate implementation of the proposal by specifically identifying the roles and responsibilities of the participating agencies. DOD also said that it would identify an executive agent to serve as a clearinghouse within DOD as part of the February 1996 plan required by the House National Security Committee.

The Department of State commented that it endorsed the need for more coordinated research and for the identification of a lead institution in U.S. government research and development (see app. II).

Both agencies provided specific technical clarifications that we incorporated in the report, as appropriate.

Scope and Methodology

We reviewed pertinent reports, documents, and legislation relevant to detection and clearance technologies. We also interviewed officials from the Office of the Secretary of Defense; the military services' program offices, laboratories, and intelligence agencies; the Departments of Energy and State; the Army Environmental Center and the Naval Explosive Ordnance Disposal Technology Division; the Advanced Research Projects Agency; the United Nations; and the National Academy of Science. We also attended related conferences and symposia and spoke with industrial and technical representatives from other countries, such as England, South Africa, Austria, Germany, and Sweden.

In May 1995, we hosted a forum to discuss landmine and other UXO problems, technologies, and solutions. Participants included representatives from the Office of the Secretary of Defense, the military services, the Departments of State and Energy, the Advanced Research Projects Agency, the United Nations, and CMS, Inc., a firm that conducted mine clearance operations in Kuwait. The key questions that the forum attempted to address were (1) whether a legitimate UXO requirement—different from the countermine requirement—exists that warrants the pursuit of technological solutions; (2) whether the research and development efforts currently planned or underway constitute a sound approach toward such a solution; (3) what factors (technical, managerial, or otherwise), if any, impede the advancement of detection and clearance technology for landmines and other UXO; (4) what change in approach to technology development (technical, managerial, or otherwise), if any, should be made in the near term and long term; and (5) who or what organizations should take the lead in instituting change and ensuring that the efforts in developing landmine and UXO detection and clearance technology are well orchestrated.

We conducted our review from September 1994 to July 1995 in accordance with generally accepted government auditing standards.

We are sending copies of this report to other interested congressional committees; the Secretaries of Defense, Energy, and State; the Secretaries of the military services; and the Secretary General of the United Nations. We will also make copies available to others upon request.

Please contact me at (202) 512-5140 if you or your staff have any questions concerning this report. Major contributors to this report were Sharon Cekala, Paul Francis, MaeWanda Michael-Jackson, and James Dowd.

Mark E Gebicke

Mark E. Gebicke, Director
Military Operations and
Capabilities Issues

Comments From the Department of Defense

Note: GAO comments supplementing those in the report text appear at the end of this appendix.

ACQUISITION AND TECHNOLOGY

OFFICE OF THE UNDER SECRETARY OF DEFENSE

3000 DEFENSE PENTAGON
WASHINGTON DC 20301-3000

August 29, 1995

Mr. Mark E. Gebicke
Director, Military Operations and Capabilities Issues
National Security and International Affairs Division
U.S. General Accounting Office
Washington, D.C. 20548

Dear Mr. Gebicke:

This is the Department of Defense (DoD) response to the General Accounting Office (GAO) draft report, "UNEXPLODED ORDNANCE: Detection and Clearance Capabilities Can Benefit From a Coordinated Approach," dated July 31, 1995 (GAO Code 703066/OSD Case 9988). The DoD generally concurs with the draft report.

On the whole, the GAO's review and subsequent publication of their findings and recommendations will afford the DoD an excellent opportunity to refocus the fragmented efforts that relate to the detection and neutralization of unexploded ordnance. Clearly, the problem is of enormous magnitude and the DoD needs to apply its limited resources in the most cost-effective manner. While the two recommendations are logical derivatives of the study, implementation will be a significant challenge, particularly from the perspective of integrating non-DoD programs into a cohesive strategy. Since technology and materiel acquisition are the centerpieces of your review, the DoD will most likely charter an existing acquisition organization with the responsibility of serving as the clearinghouse.

There are two major concerns which we encourage you to address in the final report. First, a long-term solution that was not discussed in the report is the ongoing efforts to incorporate self-destruct mechanisms in the DoD's high density munitions which would limit further proliferation of unexploded ordnance on the battlefield. Second, there is a misleading reference to U.S. forces conducting humanitarian demining operations. Such is not the case; U.S. forces train the host nation personnel to perform the demining operation. The host nation personnel are then responsible for conducting the demining operation.

See comment 1.

See comment 2.

The Department's detailed response to the recommendations is enclosed. Additional specific technical comments which should be included to improve the overall quality of the draft report were provided separately. The Department appreciates the opportunity to review the draft report.

George R. Schneiter
Director
Strategic & Tactical Systems

Attach
A/S

GAO DRAFT REPORT - DATED JULY 31, 1995
(GAO CODE 703066) OSD CASE 9988

"UNEXPLODED ORDNANCE: DETECTION AND CLEARANCE CAPABILITIES CAN BENEFIT FROM A COORDINATED APPROACH"

DEPARTMENT OF DEFENSE COMMENTS ON THE GAO RECOMMENDATIONS

*****

RECOMMENDATION 1: The GAO recommended that the Secretary of Defense include in the research and development plan called for by the House Committee on National Security a proposal on how a multi-agency clearinghouse function could be performed to

-- maintain visibility over all Federally funded research and development projects with application to detection and remediation;

-- develop an overarching strategy that encompasses both near-term and long-term priorities for detection and clearance technologies; and

-- serve as an active link to relevant international and private research and development efforts.

Now on pp. 17-18.

The GAO noted that such a proposal should be based on consultation with the Secretary of State, the Secretary of Energy, and the heads of other Federal agencies that sponsor research and development that may have application to detection and remediation of landmines, other unexploded ordnance (UXO), and other hazards. (p. 25/GAO Draft Report)

DoD RESPONSE: Concur. The DoD can prepare a proposal to accomplish the aforementioned objectives. Implementation of the proposal can be facilitated by statutory language which specifically identifies the roles and responsibilities of the various participating Federal agencies. A proposal will be included in the plan required by the House National Security Committee and will be submitted by February 15, 1996.

Now on p. 18.

RECOMMENDATION 2: The GAO recommended that the Secretary of Defense designate an executive agent to serve as a clearinghouse for research and development efforts within the DoD that may have application to detection and remediation of landmines, other UXO, and other hazards. The GAO explained that the role of such an agent would be to gain visibility over and to leverage these efforts against the broader problems of detection and remediation, rather than to champion an individual mission. (p. 25/GAO Draft Report)

DoD RESPONSE: Concur. The DoD's identification of an executive agent to serve as the clearinghouse will be provided in the plan required by the House National Security Committee language.

The following are GAO's comments on the Department of Defense's (DOD) letter dated August 29, 1995.

GAO Comments

1. A discussion of self-destruct mechanisms has been added to the report.

2. Language has been added to the report to recognize the fact that U.S. forces do not conduct humanitarian demining missions.

Comments From the Department of State

Note: GAO comments supplementing those in the report text appear at the end of this appendix.

United States Department of State
Chief Financial Officer
Washington, D.C. 20520-7427

AUG 17 1995

Dear Mr. Hinton;

We appreciate the opportunity to provide Department of State comments on your draft report, "UNEXPLODED ORDINANCE: Detection and Clearance Capabilities Can Benefit From a Coordinated Approach," GAO Job Code 703066.

If you have any questions concerning this response, please call Colonel Robert F. Carty, PM/ISP, at (202) 647-0622.

Sincerely,

Richard L. Greene

Enclosures:
As Stated.

cc: GAO - Mr. Francis
State/PM/ISP - Colonel Carty

Mr. Henry L. Hinton, Jr,
Assistant Comptroller General,
National Security and International Affairs,
U.S. General Accounting Office.

DOCUMENT 3

System/Design Trade Study Report for the Navigation of the Airborne, Ground Vehicular and Man-Portable Platforms in Support of the Buried Ordnance Detection, Identification and Remediation Technology

ADA 295760

March 1995

U.S. Army Environmental Center
Aberdeen Proving Ground, MD

Report No. SFIM-AEC-ET-CR-95043

U.S. Army Environmental Center

System/Design Trade Study Report for the Navigation of the Airborne, Ground Vehicular and Man-Portable Platforms in Support of the Buried Ordnance Detection, Identification, and Remediation Technology

March 1995

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Naval Explosive Ordnance Disposal Technology Division
Project Manager: Gerard Snyder 301/743-6855
2008 Stump Neck Road
Indian Head, Maryland 20640-5070

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13. ABSTRACT (Maximum 200 words)

This document contains a System Design Trade Study on the optimum navigation systems for airborne, ground-vehicle and man-portable Unexploded Ordnance detection platforms. This study will be used by Unexploded Ordnance Advanced Technology Demonstration decision-makers to make informed technical and programmatic decisions concerning the use of new navigation and location technologies in the detection, identification and remediation of Unexploded Ordnance.

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SYSTEM/DESIGN TRADE STUDY REPORT FOR THE NAVIGATION OF THE AIRBORNE, GROUND VEHICULAR AND MAN-PORTABLE PLATFORMS IN SUPPORT OF THE BURIED ORDNANCE DETECTION, IDENTIFICATION AND REMEDIATION TECHNOLOGY

MARCH 1995

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1.0 INTRODUCTION

1.1 Background

The United States Government is in the process of turning many defense sites back to the public for real estate development or to local governments for non-defense uses. Many of these sites are contaminated with large quantities of buried Unexploded Ordnance (UXO). The sensor technologies available on the market today for detection, mapping and remediation of hazardous materials have not been developed to the level that could be directly adapted to UXO. For instance, the Ground Penetrating Radar (GPR) needs further development for automatic adaptation to diverse soil types and various levels of energy attenuation in the ground. The difficulties are pervasive because some of the land areas have been contaminated over many decades of activity and because the nature of the land areas at distinct sites is widely diverse.

The government has instituted an Unexploded Ordnance Advanced Technology Development Program (UXO-ATD) to manage the return of Formerly Used Defense Sites (FUDS) to the public. The Naval Explosive Ordnance Disposal Technology Division (NEODTD) has been designated the technical lead organization of this program. NEODTD will be responsible for the development of reliable systems that can provide economical means of characterizing and remediating sites contaminated with UXO. This program extends from UXO detection systems, through artificial intelligence and data fusion tools, to autonomous excavation and remediation systems.

1.2 Requirement

An essential element of the detection of buried UXO is the accurate location of the ordnance so that, apart from pin-pointing potential dangers, minimal excavation is required to remove the UXO. The Government, therefore, tasked PRC with conducting a System Design Trade Study on the optimum navigation systems for airborne, ground-vehicle and man-portable UXO detection platforms. This study would be used by UXO-ATD decision-makers to make informed technical and programmatic decisions concerning the use of new navigation and location technologies in the detection, identification and remediation of UXO.

The initial navigational goals for accuracy were for 10 meters (95 percent occurrence) for the airborne systems and 0.3 meters for man-portable and ground platform systems. However, as the study progressed, it became clear that the need for navigational accuracy was driven by the requirements of the GPR sensors. The accurate positioning information required is at the ~.05m level and is essential for proper and effective focusing of GPR imaging.

The Global Positioning System (GPS) algorithms required to provide this high accuracy (0.01m-0.02m) positioning are the same for ground-vehicle, man-portable, and airborne environments. Although these algorithms are very robust, their effectiveness and success depend on the accuracy of the GPS observations. Of these three environments, the airborne platform environment is the most hostile environment for the GPS system due to electromagnetic interference, high accelerations and turbulence. This report therefore focuses on the airborne platform in order to satisfactorily cover all three platforms.

1.3 Discussion

The NEODTD tasked PRC Inc. to assist in developing the subsurface ordnance characterization system using a GPR and other sensors, together with advanced navigation techniques capable of providing very accurate positioning information. NEODTD also directed that the Center for Mapping at Ohio State University should assist PRC Inc. in developing advanced navigation techniques using the Differential Global Positioning System (DGPS).

The approaches offering a high probability of success in identification of UXO exploit data acquisition from multisensor platforms that are sufficiently flexible to adapt to the diverse soil properties prevalent at the contaminated sites. Data acquisition speeds of the different sensors need improvements for covering the hundreds or thousands of acres of contaminated sites over the entire United States. All these technologies, with the GPR being the most stringent, depend on high-rate, high-accuracy positioning data. For instance, the GPR needs positioning information at the 0.05m level with rates of ~50 Hz for proper focusing of GPR imaging and proper calibration of the radar operational parameters. Although the use of differential GPS has made it possible to obtain high-accuracy positioning, robust high-accuracy, high-rate positioning solutions are not available on the market today.

In order to achieve very high orders of accuracy from the GPS, several satellites have to be acquired simultaneously. However, since ground vehicle or man-portable systems have a reduced field of view due to horizon, landscape, buildings, or trees, this accuracy may not be attainable on a continuous basis. Such continuous accuracy is also difficult to achieve with aircraft or helicopters where maneuvers may shadow the GPS antenna from some satellites. Thus, a method of maintaining high location accuracy as satellites drop in and out is required. This could be achieved through the use of an inertial navigation system (INS). Integration of high-accuracy GPS with inertial navigation has the potential of providing high-accuracy, high-rate robust positioning for effective and proper focusing of the GPR.

The airborne GPR system operates in the frequency domain (step-chirped), which makes it possible to transmit high power over a specified range of frequencies. With high-power transmissions the signal-to-noise ratio (S/N) of the returned signals is adequate to differentiate from the background radiation. Therefore, if the GPS high-accuracy positioning algorithms are capable of providing high-accuracy (0.01m-0.02m) positioning in this high-power transmission environment, then these algorithms will perform equally well or better for the ground-vehicle or man-portable environments where the GPR transmissions are of much lower power. Furthermore, the high dynamics of the airborne environment represent the worst-case scenario for an INS. For this reason, the results of the experiments included in this report are consistently based on data collected in airborne environments. These results represent the worst-case scenario for the GPS/INS positioning of ground-vehicle, man-portable and airborne platforms.

During the reporting period between March 1, 1994 and September 20, 1994, the Center for Mapping conducted a series of concept and design studies using the GPS combined with INS for the navigation of the multisensor platforms, for the calibration of sensor parameters in quasi real-time, and for indexing sensor data position information for post-processing. The results of these studies are incorporated in this system design trade study report on the optimum navigation systems in support of buried ordnance detection, identification and remediation technology development.

Most navigation considerations are common to the airborne, ground-vehicle and man-portable platforms. For this reason the major part of this report contains a description of the GPS/INS navigation, and a performance analysis of the GPS/INS state-of-the-art technology available on the market today. Based on the results of this analysis, the different platform environments and the parameters considered, recommendations are provided for the navigation of each of the platforms (airborne, ground-vehicle, and man-portable) in section 5.

1.4 Report Format

The format of this report first presents system requirements and issues common to the different platforms (airborne, ground-vehicle and man-portable). This section is followed by specific discussions on each platform, and conclusions. The individual sections include the following: section 2 describes the functional requirements of the GPS/INS system to support the proposed UXO requirements; section 3 discusses positioning and navigation issues driving the design of the GPS/INS system and integration with other sensors, in particular the GPR system; section 4 analyzes and compares commercially available GPS and INS instruments suitable for use in UXO detection; sections 5.1 through 5.5 include analysis of the positioning and navigation issues discussed in section 3, as well as additional issues relating to the selection and use of the proposed GPS/INS instruments; section 5.6 distinguishes between the GPS/INS requirements for the different platforms (airborne, ground and man-portable) and recommends a hardware and software configuration for each platform; section 6 discusses requirements and recommendations for the moving map display software needed to support the GPS/INS navigation; and section 7 summarizes the conclusions of the report.

1.5 Conclusions and Recommendations

This System/Design Trade Study has concluded that extremely accurate positioning systems are required if maximum utility is to be made of advanced technology sensor systems. This is particularly true with GPR, where the classification of ordnance or non-ordnance is highly dependent on the accurate imaging of the system. The technologies being developed at present include GPR, magnetic and infrared sensors, and several means of integrating the multisensor data; all need accurate positioning systems. This study has shown that positioning technologies having the potential to provide high-accuracy (0.01m - 0.02m), high-rate positioning are available and include dual-frequency GPS technology integrated with INS technology.

It is recommended that the Government pursue the development of high-accuracy (0.01m - 0.02m) high-rate positioning systems. This can be accomplished by integrating GPS and INS in order to optimize the technologies available for identification, classification and remediation of FUDS contaminated with UXO. It is further recommended that the components of this high-accuracy system consist of the hardware and software identified in section 7.

2.0 FUNCTIONAL REQUIREMENTS

Navigation and sensor technologies available on the market for detection, mapping and remediation of hazardous materials have not yet been developed to the level that can be directly adapted to the UXO detection, mapping and remediation program. For instance, high accuracy (~.05m), high rate continuous GPS/INS positioning necessary for the GPR operation is not available on the market today. The technology components, however, for achieving this high accuracy, high rate positioning are available. These components need integration and testing before they can be directly adapted to the UXO detection, mapping and remediation program. The commercial markets offer a large variety of GPS and INS products and services with various levels of price, performance, accuracy and ruggedness under different operational environments. The need to accurately locate the UXO items (time and position tagging) for detection purposes and efficient remediation efforts places special navigation requirements for the different sensors used on the multisensor platform. This situation created the need for a System Design Trade Study to determine the optimum navigation systems for airborne, ground-vehicle, and man-portable platforms.

Navigational data will support UXO detection by providing quasi real-time (i.e., within 1-2 minutes) information suitable for tracking the sensor system as it traverses the survey site. This data will also support quasi real-time and post-processing of the sensor data (with the GPR being the most stringent). Of significance is the fact that the navigation system operates in a relatively hostile environment. This includes electro-magnetic interference (EMI) from the GPR and any local transmitters (e.g., TV, radio, aircraft radar), transmission path obstructions such as trees cutting off GPS satellite signals, vibration and flight turbulence.

The requirement for GPS/INS positioning in the UXO-ATD Program is threefold:

- Navigation of the moving platform.
- Quasi real-time positioning for sensor calibration.
- Indexing of the sensor data to positioning for post-processing.

The navigation requirements of the UXO detection system are driven by the necessity of accurately locating buried objects at the surveyed site. The sensors used to locate the buried objects (including the GPR system) must perform a complete coverage of the surveyed area. This is accomplished by moving the sensors along predefined survey lines. The separation of these survey lines and the spacing between discrete sensor data points are determined by the sensor characteristics. For the GPR, for instance, the ideal separation of data points, both in line and between adjacent lines, is between 1/12 and 1/4 of the shortest wavelength of radar energy to support coherent focusing of the energy return information. Accurate positioning information is also required for calibration to maintain the accuracy of the sensor itself as the survey is performed.

High accuracy quasi real-time positioning is required to calibrate the GPR for a variety of parameters before surveying a particular site. The quasi real-time positioning will allow the field operator to process the GPR data with an approximate one minute delay, to evaluate the quality of the GPR data and, if necessary, to make adjustments to the parameters controlling the GPR operation.

The final role of GPS is to index the GPR data with position information for post-processing. Positioning at rates up to and including the GPR data rates will result in more accurate GPR data post-processing. This role of the GPS system alone does not necessitate GPS position information in real-time. GPS position information is only required for post-processing. As mentioned above, quasi real-time GPS positioning is required only for GPR calibration.

All of the above roles call for uninterrupted GPS/INS positioning at 10-90 Hz rates with an accuracy at the .05 - 0.15m range. Section 5.1 contains descriptions of the accuracy, the data rate requirements and their relationships for all three platforms (airborne, ground and man-portable).

This study was conducted taking into consideration that the solutions to meeting navigation requirements should maximize use of Commercial Off the Shelf (COTS) products and, where possible, minimize the need for new technology or equipment development.

3.0 DISCUSSION OF POSITIONING AND NAVIGATION ISSUES

The positioning and navigation issues that will be addressed are the following:

1) Interference between GPS and GPR;
2) Slow GPS standard data rates;
3) Integration of GPS/INS for uninterrupted position information when GPS signals are not available.

The effects of these issues on the different platforms are described in sections 5.1 through 5.5.

3.1 Interference Between GPS and GPR

High accuracy cm-level positioning in both real-time and post-processing requires use of dual-frequency (L1 and L2) carrier phase measurements. The carrier phase measurements are accurate at the mm-level; however, these measurements lack the geometric strength required for the cm-level positioning of the moving GPS receiver. This is the result of the inherent integer ambiguities affecting the carrier phase measurements. Real-time and post-processing cm-level positioning requires resolution of the integer ambiguities affecting the carrier phase measurements (see Appendix A).

Real-time ambiguity resolution is based on a small number of measurements. Consequently, the noise and the systematic errors affecting the measurements will be at the few cm-level. Therefore, the moving GPS receiver should be able to operate in a moderate noise environment. For this reason interference tests between the GPS and the GPR systems were conducted between September 17-21, 1994, at Jefferson Proving Ground in Madison, Indiana. The results of those tests are described in section 5.6.1. The GPR system used in those experiments was designed for airborne applications. The airborne GPR systems operate in the frequency domain (step-chirped system) which makes it possible to transmit high power over a specified range of frequencies. With high power transmissions the S/N ratio of the returned signals is adequate to differentiate them from the background noise.

When the radar was transmitting at approximately ±10 MHz of the frequencies whose third harmonics are the L1 (1575.42 MHz) and L2 (1227.6 MHz) GPS frequencies, the tracking of the GPS signals was interrupted completely. The operation of the GPR used in these experiments did not allow complete deactivation of the interfering frequencies. Its operation allowed only minimization of the time allocated for the transmission of those frequencies. When this time was minimized, the GPS receivers were able to track the L1 signals for all of the satellites in view and the L2 signals for only 2 or 3 out of the 7 or 8 available satellites.

The L2 is a weaker signal and because of Anti-Spoofing (AS) the L2 pseudo ranges and carrier phases are recovered through cross-correlation. Cross-correlation is a noisier process and as a result, the tracking of the L2 signal is more difficult in a noisy and interfering environment. Missing L2 data for most of the satellites will be detrimental to high accuracy positioning both in real-time and in post-processing. To solve this problem the GPR should be equipped with filters that will eliminate completely the transmission of the interfering frequencies. (See section 5.6.1.)

3.2 Slow GPS Standard Data Rates

The data rate requirements for calibrating the GPR system in real-time, and for indexing the GPR data with position information for post-processing are in the range of 10 to 90 Hz (section 5.1). The commercial dual-frequency GPS receivers available on the market today are capable of providing data (pseudo ranges and carrier phases) at a rate of 2 Hz (i.e., twice per second). One solution to this problem is to use doppler and doppler rates to predict the position of the moving GPS receiver at the 10 to 90 Hz rates. The success of this solution depends on the ability to model the dynamics of the moving GPS receiver during the interpolation interval using doppler and doppler rates.

If the dynamics of the moving GPS receiver cannot be modeled with doppler and doppler rates, then it may be possible to modify the GPS receivers to output the GPS data at their internal measuring rate which for most receivers is in the order of 50 Hz. Having GPS data at a 50 Hz rate will allow accurate GPS positions tobe calculated. This rate, however, will not be adequate for all of the GPR requirements (section 5.1). Note that at these high rates, the GPS observations will be much noisier. A third approach, which is the recommended approach, is to integrate the GPS system with an INS system, which will provide not only the required 90 Hz rates but also navigation during the periods when the GPS signals are not available due to obstructions.

3.3 Integration of GPS/INS for Uninterrupted Position Information

Integration of GPS and INS will ensure uninterrupted positioning in quasi real-time, and in post-processing. The positioning accuracy during periods when GPS measurements are not available depends on the accuracy of the INS and on the length of time that GPS measurements are not available. For instance, a low-cost INS (e.g. LN-200 ~$40,000) will provide accuracies at the 0.5m to 1.0m level in post-processing (smoothing) and 3.0m to 6.0m in real-time (filtering), when the GPS signals are obstructed for about 3 minutes (Figure 9). However, a high quality INS (e.g. LN-100 ~$100,000) will provide accuracies at the 0.01m to 0.05m level in post-processing (smoothing) and 0.1m to 0.2m in real-time (filtering) when the GPS signals are obstructed for the same period (Figure 10). When the GPS signals are not available for longer periods, the positioning information degrades exponentially in both real-time and post-processing with a lower rate of degradation in post-processing due to smoothing. Quasi real-time processing will allow smoothing of the INS positioning. For the calibration of the GPR only quasi real-time positioning is required, thereby making it possible to provide smoothing accuracies for GPR calibration in quasi real-time.

Integration of GPS with INS is very important for the airborne platform because it will provide the required higher positioning rates of 10 to 90 Hz without any need to modify the GPS receivers. It will also provide the capability to recover from short losses of lock due to the dynamics of the airborne platform. Furthermore, the INS system will serve as a backup positioning system to minimize loss of information when GPS signals are not available for any unforeseen reasons.

The INS can also provide for the translation of the GPS antenna's location to GPR antenna phase center. This will allow for more flexibility in mounting the GPS antenna relative to the GPR.

4.0 PERFORMANCE ANALYSIS AND COMPARISONS OF GPS AND INS INSTRUMENTS

4.1 Global Positioning System

High accuracy positioning of airborne platforms both in real-time and in post-processing requires use of dual-frequency GPS receivers. The speed and the effectiveness of high accuracy positioning depends to a large extent on the quality of the dual-frequency GPS receivers. For this reason, the Center for Mapping analyzed the quality of the dual-frequency GPS data for Ashtech, Trimble, and Allen Osborne Turbo-Rogue GPS receivers. Ashtech, Trimble and Turbo-Rogue dual-frequency receivers are the leading brands for commercial dual-frequency GPS receivers on the market today. The noise characteristics of the dual-frequency GPS data from these three receivers have been analyzed to determine the expected number of epochs required for On-The-Fly (OTF) ambiguity resolution. This is the number of epochs required to initialize high accuracy positioning after recovering from losses of lock to the GPS signals. A mathematical model for GPS OTF ambiguity resolution is presented in Appendix A.

4.1.1 Approaches/Characteristics

The following three sections contain the analyses of the Ashtech, Trimble and Turbo-Rogue data on the basis of the instantaneous and average values of the estimated widelane[1] ambiguities. As described in Appendix A, the speed and success of the OTF ambiguity resolution depends on the estimated widelanes, the geometry-free carrier phase combination and their accuracies. The accuracy of the geometry-free carrier phase combination is at the low (3-5) mm level and is about the same for all the GPS dual-frequency receivers. The accuracy of the widelane ambiguities, however, depends on the accuracy of the code pseudo ranges, which is a function of the receiver technology. For this reason, the analysis of the dual frequency GPS receiver is based on the analysis of the estimated widelane ambiguities. The data analyzed was from kinematic surveying in the U.S. (Ashtech in New Jersey, Trimble & Allen Osborne in

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[1] The dual-frequency GPS receivers record pseudo-ranges and carrier phases. The carrier phases have wavelengths of 19 cms and 24 cms. When these two phases are subtracted, the resulting phase is called widelane and has a wavelength of 86 cms. When a GPS receiver locks into a satellite signal, it initializes the carrier phases by assigning an arbitrary number to the initial phase measurements. This number changes only when the GPS receiver loses and regains lock to the satellite signal. Carrier phase integer ambiguity refers to the difference of this arbitrary number from the actual number of wavelengths between the phase center of the GPS antenna of the ground receiver and the phase center of the satellite GPS antenna. When these carrier phase integer ambiguities are related to the widelane, they are called widelane integer ambiguities.

California). The stationary and moving receiver data were collected simultaneously to determine the characteristics of interest in receiver selection.

Analysis of Ashtech Dual-Frequency GPS Data

Figures 1, 2 and 3 show the instantaneous and average widelane values for a stationary and a moving receiver for elevation angles ranging from 10 to 80 degrees.

Figure 1 shows the instantaneous and average values of the widelane ambiguities for elevation angles of 53 to 83 degrees. At these high elevation angles the average value of the widelane ambiguities for the stationary receiver varies between 0.0 and 0.21 widelanes. The average widelane variation of the moving receiver at those elevation angles varies between 0.92 and 0.10 widelanes.

It is also clear that the epoch-to-epoch widelane ambiguity of the moving receiver (airplane data used in this analysis as worst case) exhibits a linear trend which seems to be converging at the -.84 value after about one hour of operation. This value is approximately -2 widelanes away from 1.12 value which would require 5 widelanes search (±2 widelanes). This interval search may take several minutes to converge.

It is evident from figure 1 that the Ashtech data is internally filtered. As a result, the recorded observations are correlated. Therefore, averaging the estimated widelanes will not work because the average will converge to a different value than the actual widelane value as clearly seen in figure 1. In this figure the epoch-to-epoch widelane ambiguities converge at the -.84 value whereas the average widelane ambiguity converges at the -0.05 value. This is the reason why the quality of the Ashtech data is judged on the basis of the epoch-to-epoch estimates of the widelane ambiguities rather than on their average values.

Figure 2 shows the instantaneous and average values of the widelane ambiguities for both the stationary and the moving receivers for elevation angles of 31 to 61 degrees. At these elevation angles the widelane ambiguity of the stationary receiver varies between –0.44 and +0.91 widelanes. For the moving receiver the widelane ambiguity varies between -0.96 and 0.65 widelanes. In this case, the searching interval should be within ±2 widelane which will take several epochs to converge.

Figure 3 shows the instantaneous and average values of the widelane ambiguities for the stationary and the moving receivers for elevation angles of 11 to 34 degrees.

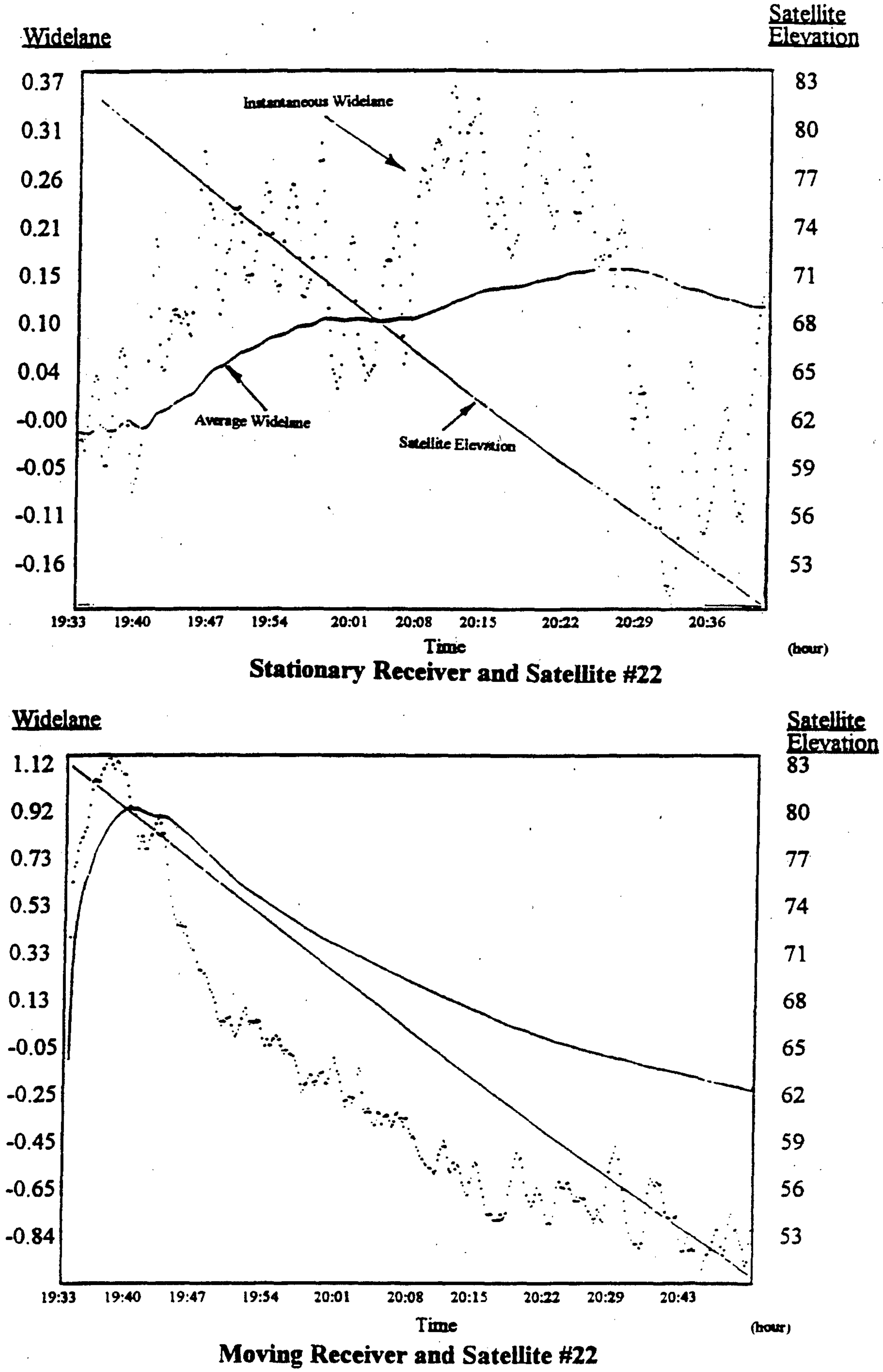
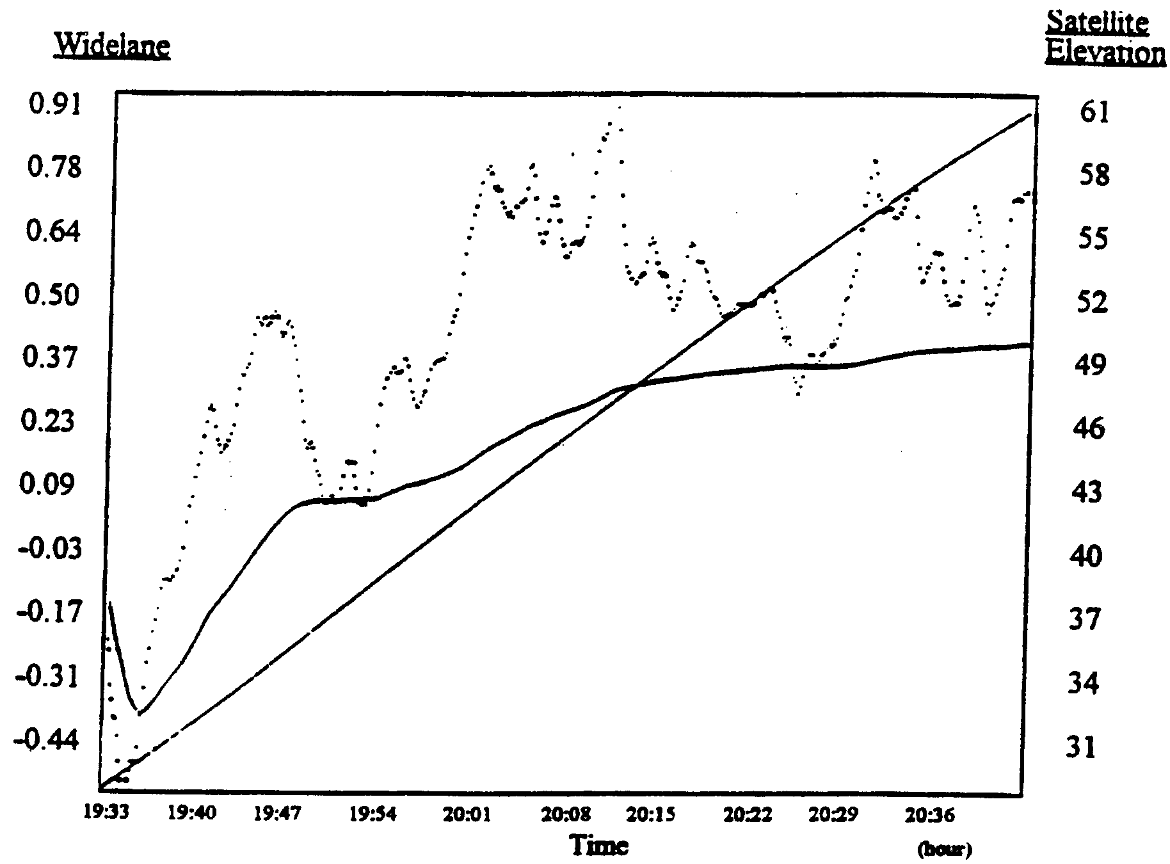
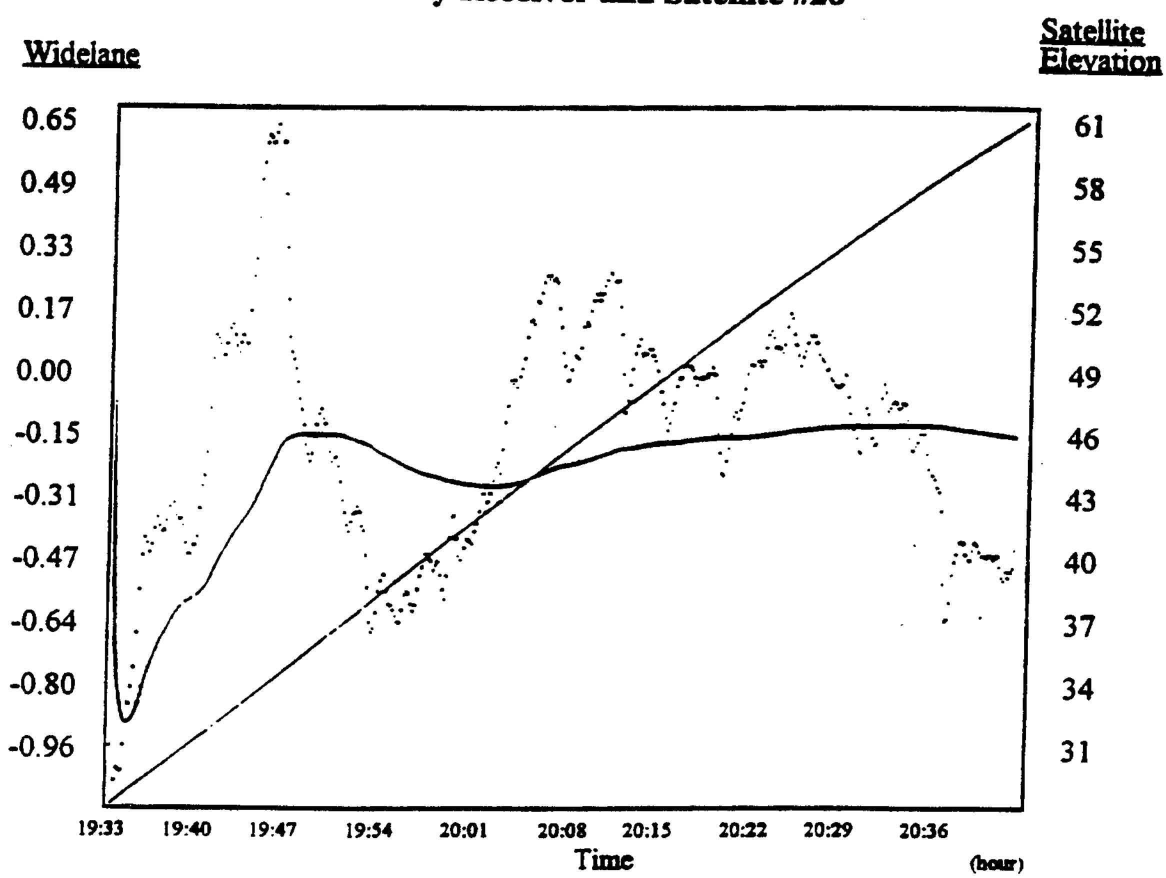


Figure 1- Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite #22

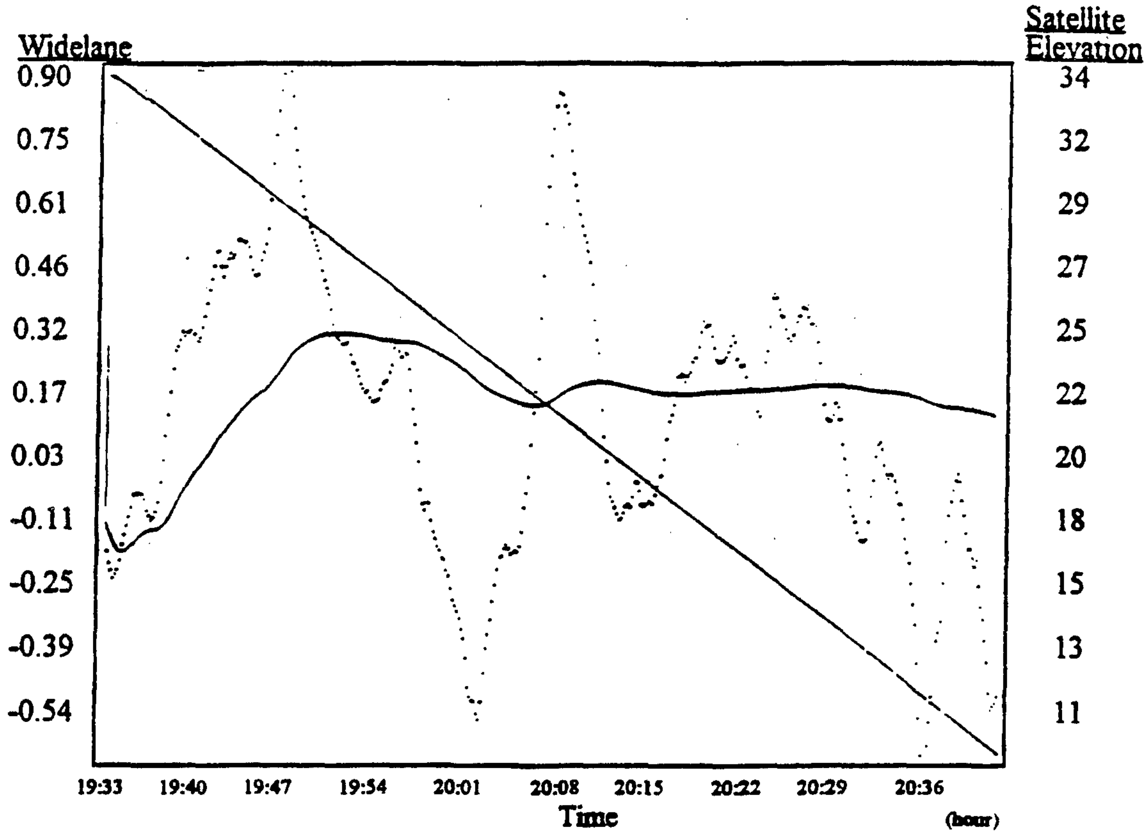


Stationary Receiver and Satellite #28

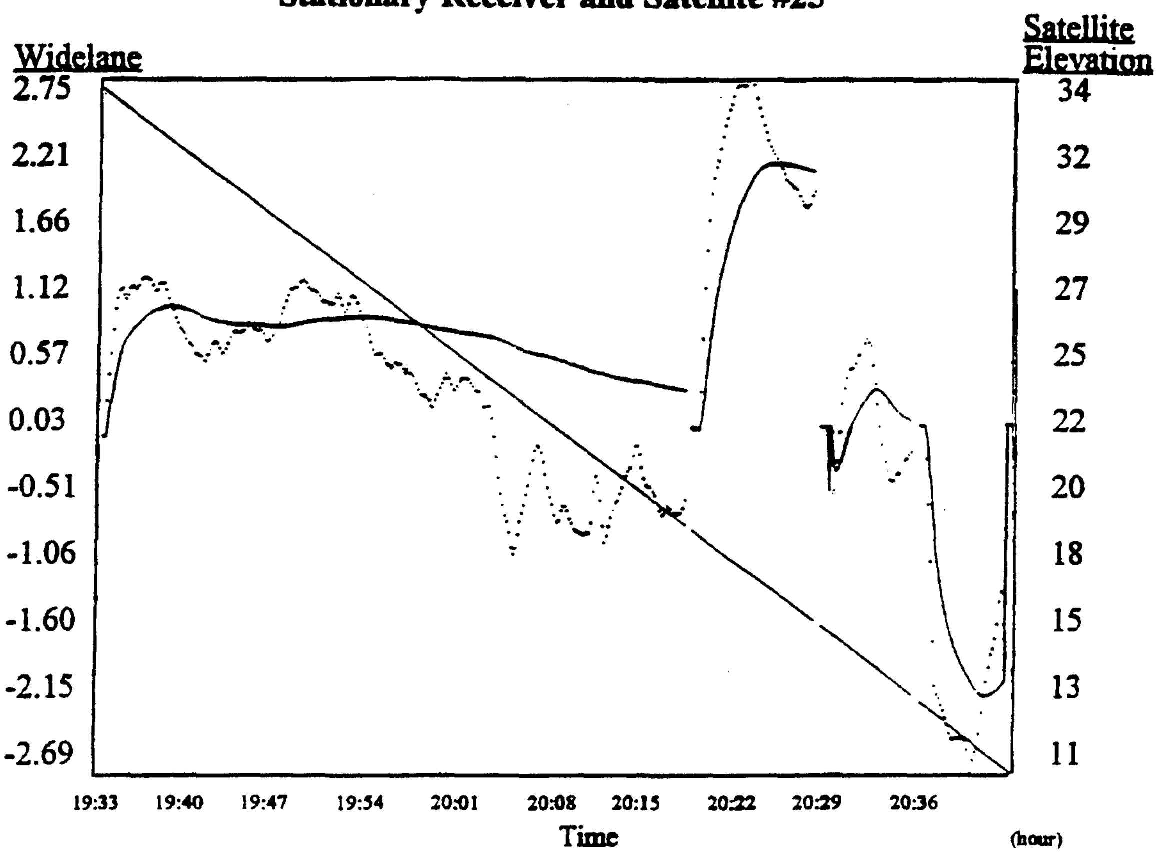


Moving Receiver and Satellite #28

Figure 2 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite #28



Stationary Receiver and Satellite #25



Moving Receiver and Satellite #25

Figure 3 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite #25

At these elevation angles the widelane of the stationary receiver varies between -0.54 and 0.90 widelanes whereas the widelane ambiguity for the moving receiver varies between -2.69 and 2.75 widelanes. The reason for the large widelane variations is the presence of cycle slips and the low elevation angles. Furthermore, for elevation angles of 20 to 30 degrees the variation of the widelane ambiguities is about 2 widelanes which will also require a search interval of ±3 widelanes and several minutes to converge.

It is obvious from the above figures that the Ashtech receivers filter their pseudoranges internally to the extent that the widelane ambiguity converges to the correct value after 10 to 20 minutes of continuous tracking. Furthermore, for elevation angles of 25 degrees or less the behavior of the widelane ambiguity is not very good (i.e., there are numerous cycle slips and the ambiguity does not seem to converge to an integer value).

Analysis of Trimble Dual-Frequency GPS Data.

Figure 4 shows the instantaneous and average widelane values for both a stationary and a moving Trimble receiver for elevation angles ranging from about 17 to 84 degrees.

It is evident from this figure that the widelane variation is ±1 for the stationary receiver and ±2 for the moving receiver. Furthermore, the average widelane values of both the stationary and the moving receiver vary by at most 1 widelane for elevation angles above 30 degrees. This is also true for lower elevation angles down to 20 degrees if losses of lock are handled properly. Furthermore, for both the moving and the stationary receiver the average value of the widelane ambiguity converges to the correct value after 1 to 2 minutes of data. Having the widelane ambiguities to an accuracy of one cycle, OTF ambiguity is very fast and effective even with as few as five satellites in view.

Comparing figures 1, 2, and 3 with figure 4 it is obvious that the Trimble data is not filtered and that the average value of the widelane ambiguities converges to the correct widelane value with 1 to 2 minutes of data. This is very important when one or both of the receivers experience frequent losses of lock.

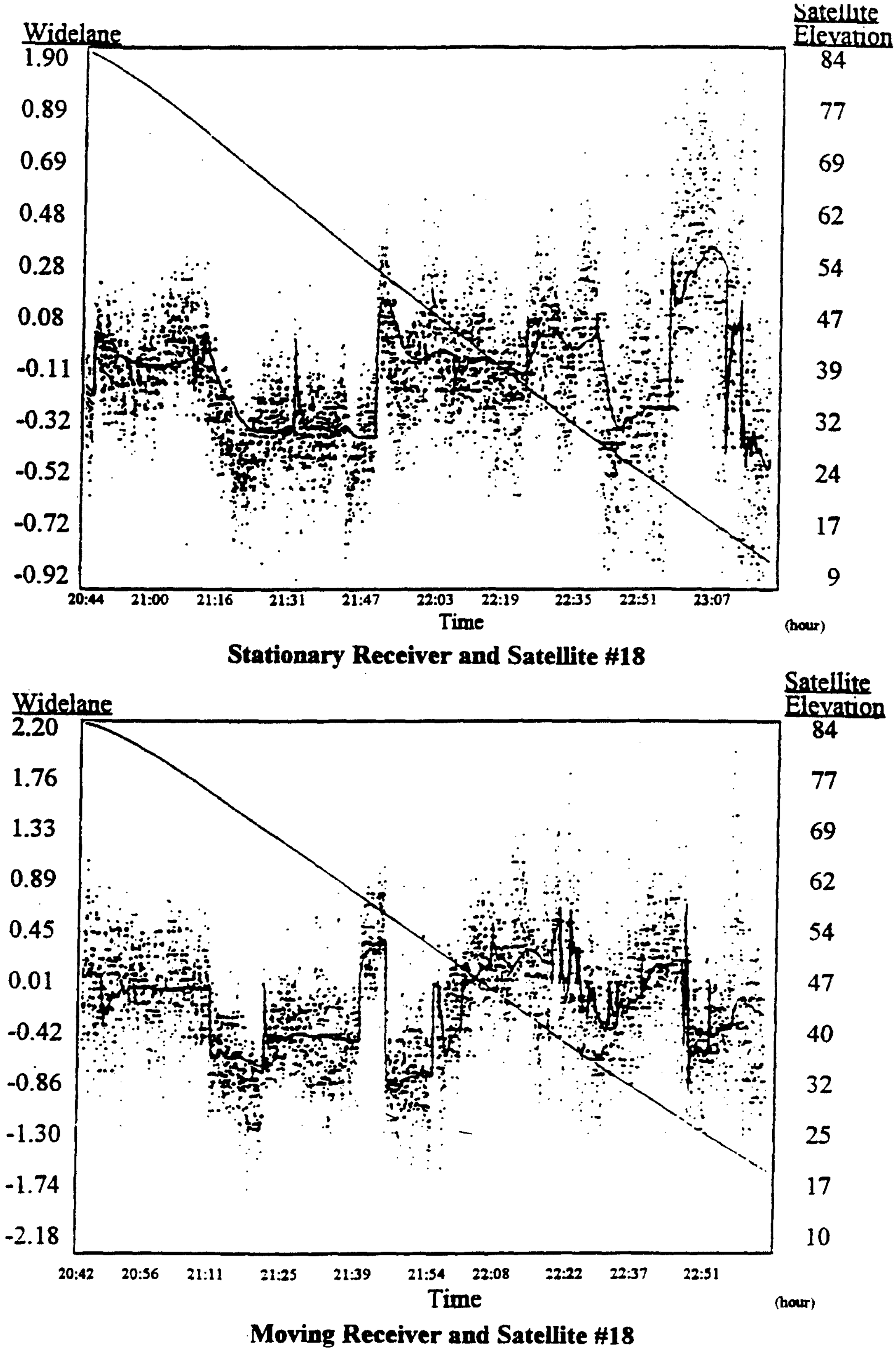


Figure 4 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite #18

Analysis of Turbo-Rogue Dual-Frequency GPS Data

Figure 5 shows the instantaneous and average values of the widelane ambiguities for both the stationary, and the moving receiver for elevation angles of 59 degrees to 66 degrees. The instantaneous values of the widelane ambiguities vary by 2 widelanes for the stationary receiver and by 4 widelanes for the moving receiver. The average values of the widelane ambiguities, however, vary by 1 widelane for the stationary receiver and by 2 widelanes for the moving receiver. The convergence to the correct widelane ambiguity takes about 2 to 3 minutes of continuous tracking. Therefore, if data is available continuously for 2 to 3 minutes, the widelane can be estimated directly without any need for ambiguity resolution. If loss of lock occurs within that time period, an ambiguity search should be performed before cm-level positioning can be resumed.

Figure 6 shows the instantaneous and average values of the widelane ambiguities for the stationary and the moving receiver for elevation angles of 35 to 56 degrees. The variation of the instantaneous and average widelane ambiguities for both the stationary and the moving receiver seems to exhibit the same behavior as that for figure 5.

Figure 7 shows the instantaneous and average values of the widelane ambiguities for a stationary and for a moving receiver for elevation angles ranging from about 5 to 50 degrees. The range of the widelane ambiguities for the stationary receiver is 1 widelane for elevation angles above 30 degrees and 2 widelanes for elevation angles of 15 to 30 degrees. The average value of the widelane ambiguity converges to the correct value with 1 to 2 minutes of data. In the neighborhood of cycle slips the average value of the widelane ambiguity varies by 1 widelane for elevation angles above 30 degrees, and by 2 widelanes for elevation angles of 15 to 30 degrees. With only one widelane uncertainty the ambiguity resolution is fast and very robust.

For the moving receiver the instantaneous widelane ambiguity fluctuates by 3 widelanes and the average widelane ambiguity fluctuates by less than 1 widelane, 1 to 2 minutes away from a cycle slip. In the neighborhood of a cycle slip the widelane ambiguity fluctuates by one to two widelanes. Therefore, one minute averaging will yield an uncertainty of one widelane which in turn will warranty fast and robust ambiguity resolution.

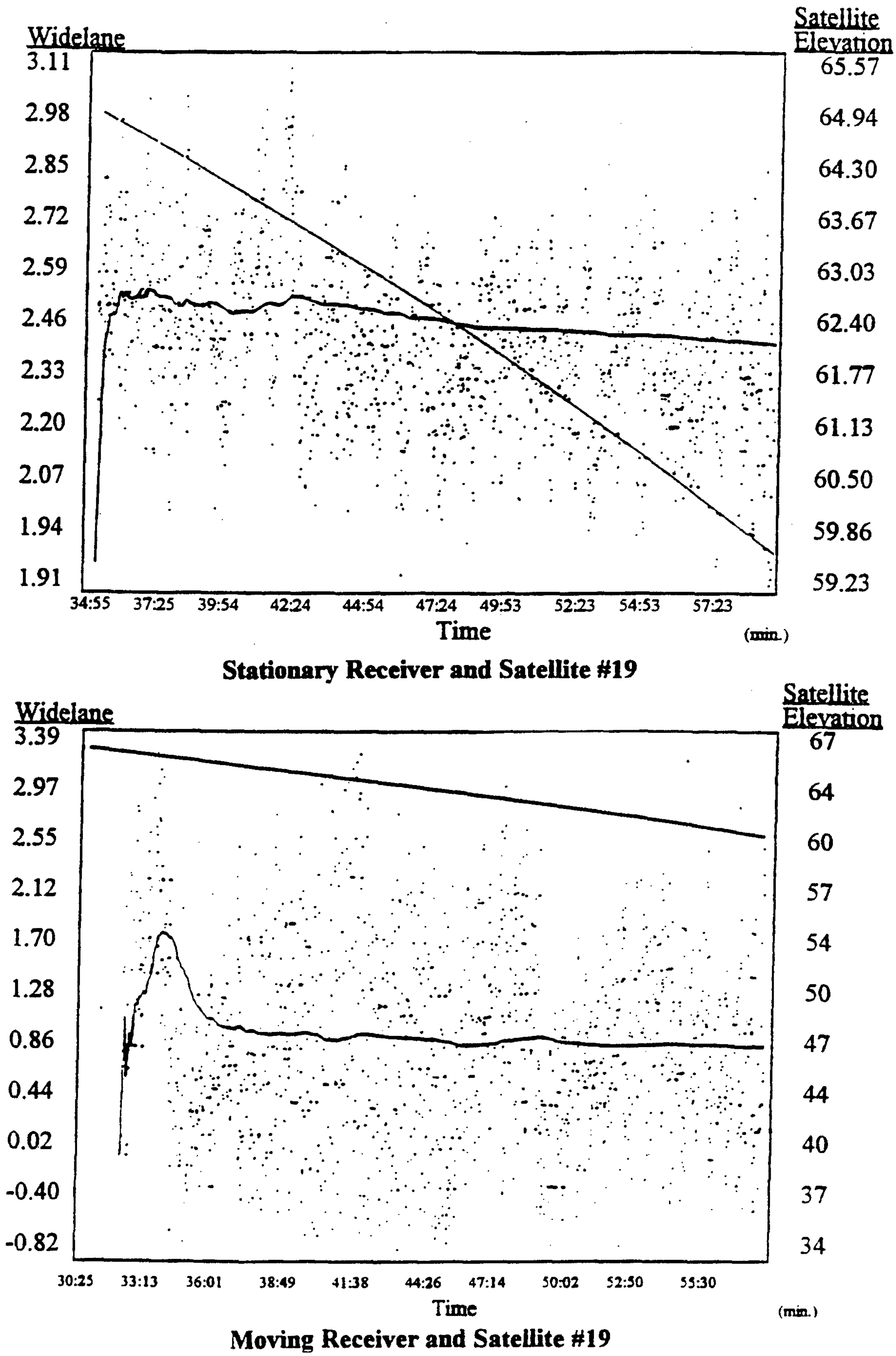
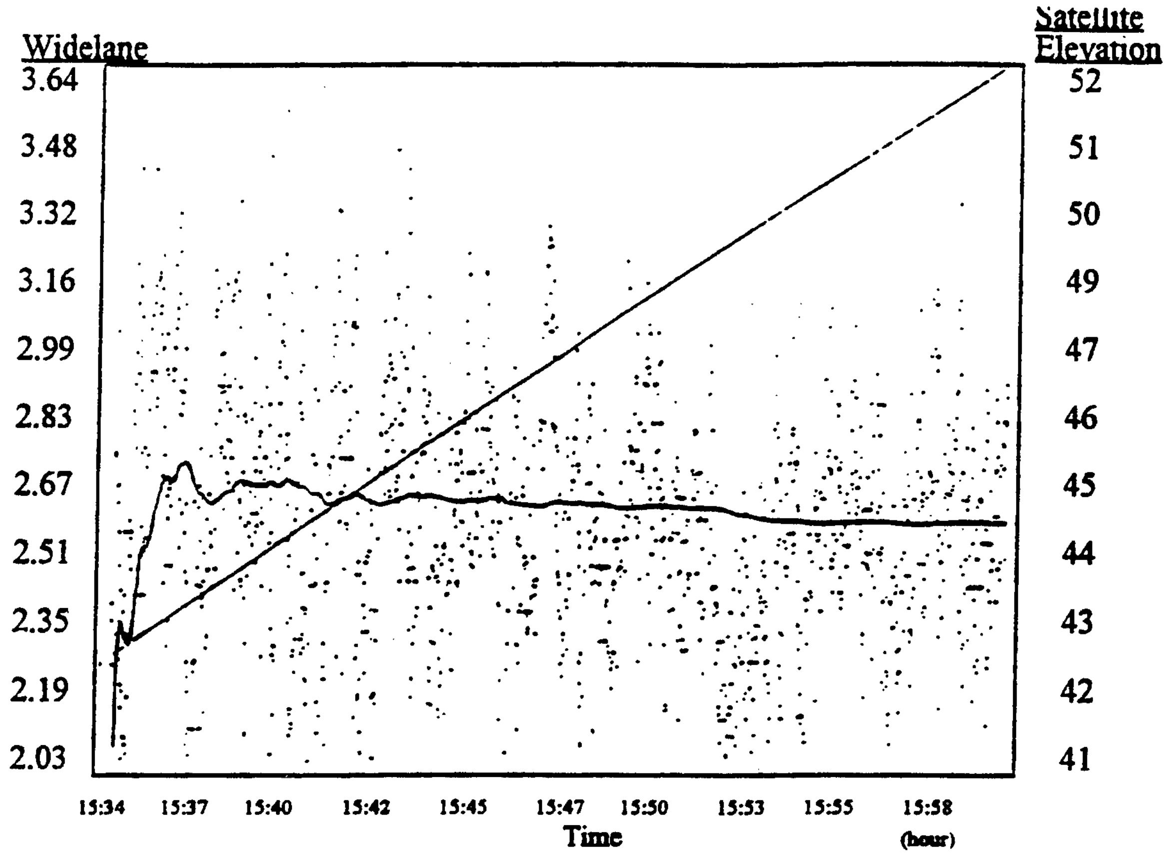
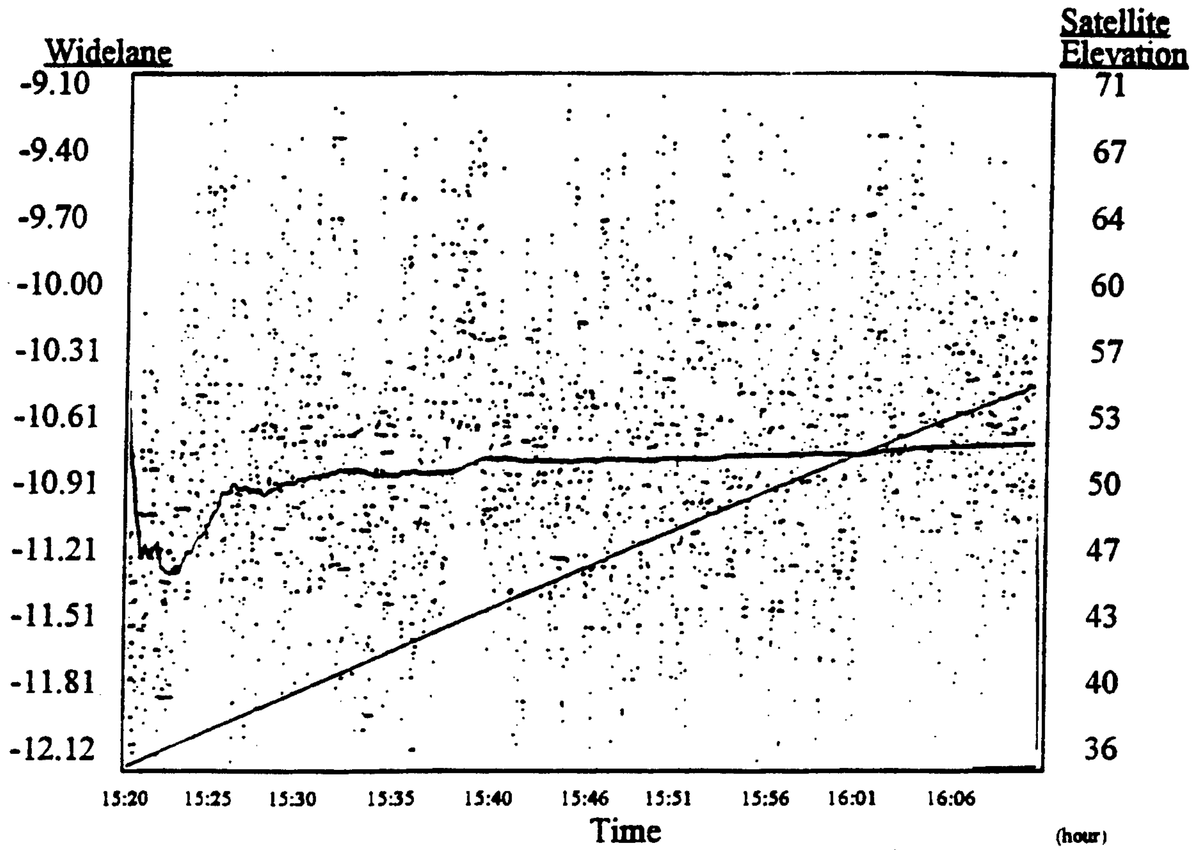


Figure 5 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite #19

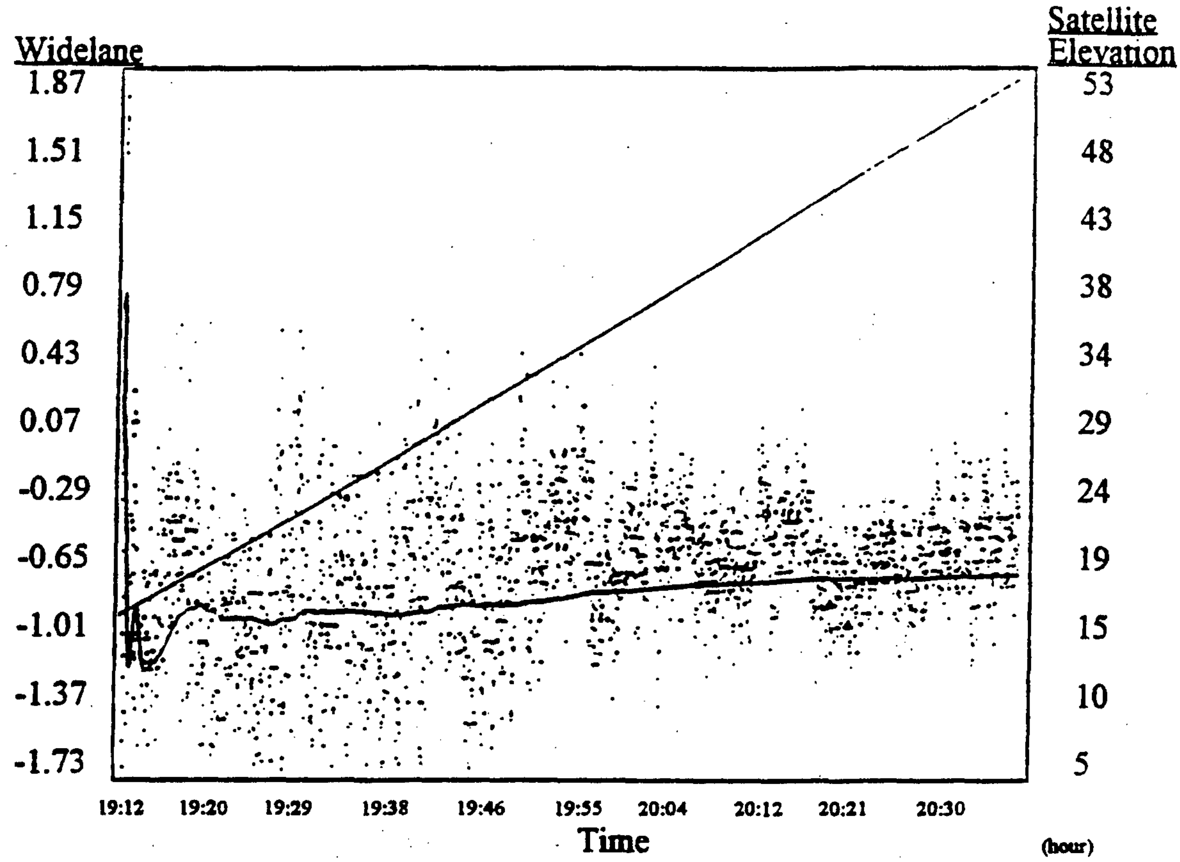


Stationary Receiver and Satellite #2

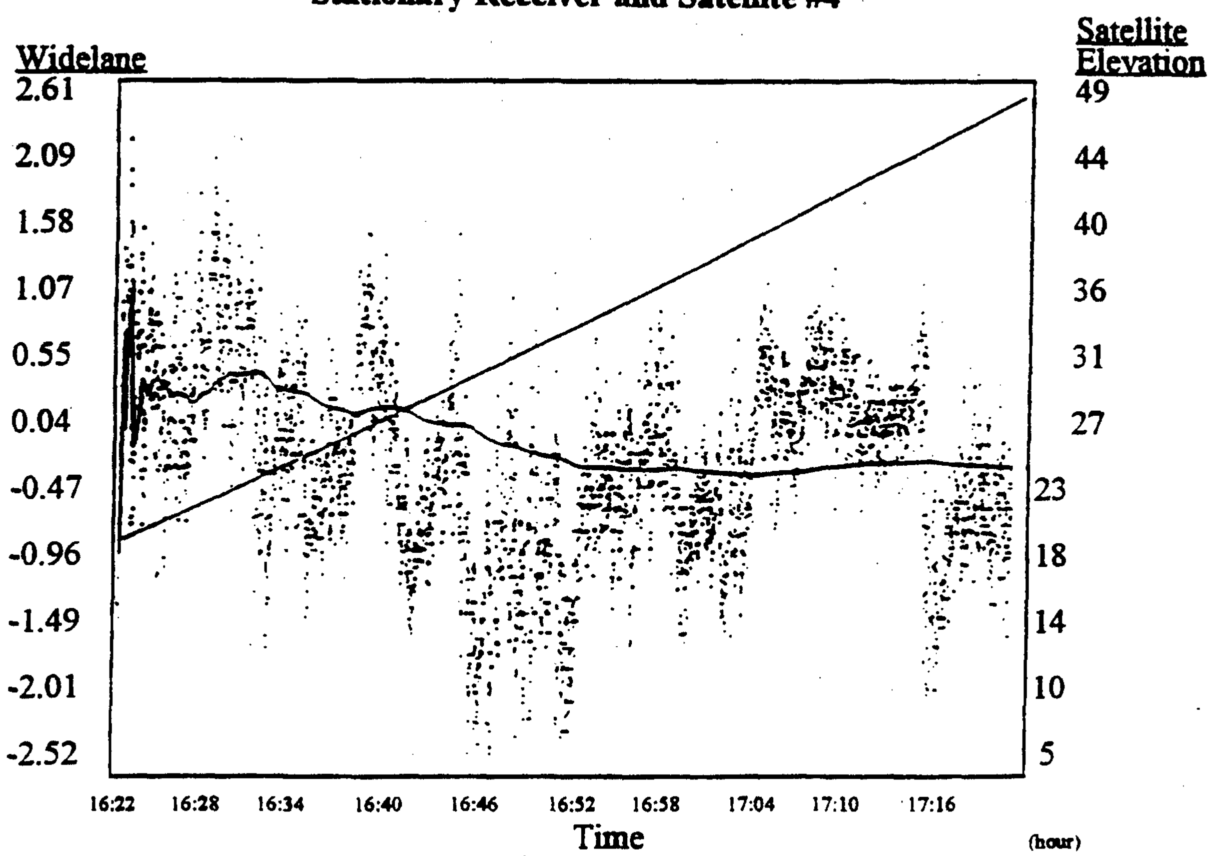


Moving Receiver and Satellite #2

Figure 6 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellite # 2



Stationary Receiver and Satellite #4



Moving Receiver and Satellite #7

Figure 7 - Instantaneous & Average Widelane vs. Satellite Elevation & Time - Satellites #4 & #7

Ground Plane Consideration

For all of the results described in the previous sections the stationary receivers were equipped with a geodetic antenna which is protected with a ground plane. The moving receivers, however, were equipped with an airplane antenna which is not protected with a ground plane. Furthermore, the quality of the data does not seem to be better when the airplane was parked on the taxi way. This suggests that the reason for having worse data from the moving receivers is the absence of the ground plane from the airplane antenna. For the airborne platform an airplane antenna must be used with the understanding that the GPS data will be noisier due to the dynamics of the airplane and the presence of multipath. For the ground and man-portable platforms the moving receiver should be equipped with a geodetic antenna.

4.1.2 Recommendation

The quality of the GPS data from Ashtech, Trimble, and Turbo-Rogue receivers was investigated using instantaneous and average values of the widelane ambiguities. A summary of the results is given in table 1. The speed and reliability to estimate the widelane ambiguities will determine the robustness of the real-time and post-processing GPS cm-level positioning.

From this analysis it is clear that Ashtech receivers filter the data internally. As a result the recorded pseudoranges are correlated, and therefore additional filtering or averaging will not be effective in speeding up the estimation of the widelane ambiguities. Consequently, one should wait until the internal filtering yields the widelane ambiguity to within one cycle. The time it takes for the filter of the moving receiver to converge to 1 widelane uncertainty is 10 to 20 minutes long, which will make it very difficult to recover from losses of lock. For the stationary receiver, however, the estimated widelane ambiguities seem to have an uncertainty of 1 to 1.5 widelanes, which is a good range for OTF ambiguity resolution.

It is also clear from the GPS data analysis that the Trimble, and Turbo-Rogue receivers do not filter their data internally. As a result the instantaneous widelane ambiguities are uncorrelated and they can be filtered or smoothed optimally to yield values with one widelane uncertainty, in which case OTF ambiguity resolution is fast and effective. The time it takes to filter the widelane ambiguities to an accuracy of one widelane is about 1 to 2 minutes for both the Trimble and Turbo-Rogue receivers. From the analysis of Ashtech, Trimble, and Turbo-Rogue GPS data it is recommended that either Trimble, or Turbo-Rogue receivers, equipped with geodetic GPS antennas should be used for the base stations. For the airborne platform, an airplane antenna should be employed; for the ground and man-portable platforms, a geodetic antenna should be used.

Table 1
Summary of Receiver Comparison

	Ashtech		Trimble SSE		Allen Osborne Turbo-Rogue	
	Stationary	Moving	Stationary	Moving	Stationary	Moving
Low elevation widelane ambiguity (widelanes)	-0.54 +0.90	-2.69 +2.75	-0.92 +1.09	-1.30 +2.00	-1.73 +1.87	-1.49 +2.09
High elevation widelane ambiguity (widelanes)	-0.44 +0.91	-0.96 +0.65	-0.72 +0.48	-1.30 +0.89	-1.37 +0.43	-2.52 +1.07
Average widelane (widelanes)	N/A due to internal filtering	N/A due to internal filtering	+/-1	+/- 2	+/-2	+/-2
Convergence	10 - 20 minutes		1 - 2 minutes		2 - 3 minutes	

4.2 Inertial Navigation System

Aiding of GPS positioning with inertial navigation is needed to provide navigation and positioning information during the periods when the GPS signals are not available due to obstructions. Furthermore, accurate image focusing of the GPR requires positions at a rate of 10-90 Hz (section 5.1). The commercial GPS receivers available on the market today provide positions at a rate of at most 2 Hz. A combination of GPS with an INS is capable of providing positioning information at a rate of up to 200 Hz, which more than covers the requirements of the GPR.

During the reporting period the Center for Mapping conducted a covariance analysis to establish the accuracy requirements of INS for high accuracy positioning rates between GPS fixes, and high accuracy positioning during the periods when the GPS signals are not available due to obstructions. In this covariance analysis it was assumed that 0.03m level GPS positions will be available at a rate of 1 position every 10 seconds, with missing GPS data for periods of up to 5 minutes. During GPS outages (periods with missing GPS data due to obstructions), the navigation of any of the platforms will rely on an INS, corrected with the error models as revised from the last GPS updates.

Approaches/Characteristics

For the purpose of this analysis it is sufficient to assume that the system has nominal, essentially constant motion with respect to the earth's surface, which means that the latitude, longitude, and height rates are zero. For covariance analysis, this assumption does not cause substantially different results from more realistic assumptions of motion. The sampling rate is assumed to be 2 Hz, and the total time interval for the analysis is arbitrary since the Kalman filter is a recursive filter. Appendix B provides a discussion on the mathematical models used in evaluating inertial navigation capabilities.

The INS for this analysis was assumed to be a strapdown system oriented with ring laser or fiber optic gyros; the accelerometers are usually of force-rebalance type. Table 2 lists the types and the values of the errors considered in the covariance analysis. These errors are assumed to cover, or dominate, the multitude of sensitivities of the instrument in an environment of moderate dynamics and controlled temperatures. The error budget for a particular system is more detailed since it depends on the specific vibration/shock and temperature isolation mechanisms available, as well as the specific idiosyncrasies of the particular sensor. Consideration of more than just the basic error parameters is, therefore, beyond the present scope of this investigation. In addition, the unique calibration problems and the dynamic motion induced gyro errors of strapdown systems are ignored as they are also to some extent mission dependent. As mentioned above, the GPS position updates are taken as direct observations of position with the errors modeled as white noise. The initial errors in the states were assumed to be given by the standard deviations corresponding to the values in table 2 for the position and bias states. For the velocity, it was assumed to be 0.005m/sec; and for the orientation angles, it was taken as 8 arc-seconds for the level components and 130 arc-seconds for the heading.

Figure 8 shows the accuracy of the platform positions in east, north and down directions as a function of time. In this figure the GPS positions are assumed to have an accuracy of 0.03m with an update rate of 0.1 Hz (one position every 10 seconds). It is evident from this figure that the accuracy of the INS positions deteriorates exponentially between GPS updates, and that the maximum error between the GPS updates decreases to a steady-state value after about 200 seconds.

Table 2

Parameter Values used in Simulation

IMU(INS)		(LN-100)	(LN-200)
	Accuracy	Medium-High	Low
Accelerometer			
	bias error	25mgal =: 25 μg	200mgal =: 200 μg
	scale factor error	120 ppm	300 ppm
	white noise	8 mgal/√Hz	50 mgal/√Hz
Gyros			
	drift bias error	0.003 / √hr	1. / √hr
	white noise	0.0055° / √hr	0.07°/ √hr
Platform Position Updates Using GPS			
	period:	0.1 Hz	0.1 Hz
	precision:	3 cm	3 cm

Figures 9 and 10 show the interpolation capability of two types of instruments, one of low accuracy (i.e., LN-200) and one of medium to high accuracy (i.e., LN-100) system. The low accuracy system, which is also a low cost system (~$40,000), can maintain an accuracy of ~.5 meters in free-inertial (i.e., filtering) mode and ~.1 meter in smoothing mode for about one minute without any GPS fixes. For longer GPS outage periods (e.g., 5 minutes or more) the low cost system can maintain an accuracy of 21.28 meters in free-inertial (i.e., filtering) mode and 3.45 meters in smoothing mode. The high accuracy systems (higher cost, ~$100,000), can maintain an accuracy of .569 meters in free-inertial (i.e., filtering) mode and an accuracy of .1 meter in smoothing mode when GPS signals are not available for about 5 minutes.

For an airborne system the expected periods of GPS outages will be in the order of several seconds. Therefore a low cost, low accuracy inertial system will provide the .07m accuracy requirements in both quasi real-time and in post-processing.

Recommendation

From the covariance analysis for the integration of GPS with INS, it was evident that ~0.1m navigation without GPS is possible for periods of up to 1 minute (smoothing mode) with a low accuracy system and for periods up to 5 minutes with a high accuracy system. As described in section 5, the LN-200 (low accuracy) system is recommended for the airborne and the man-portable platforms, and the LN-100 (high accuracy) system is recommended for the ground platform.

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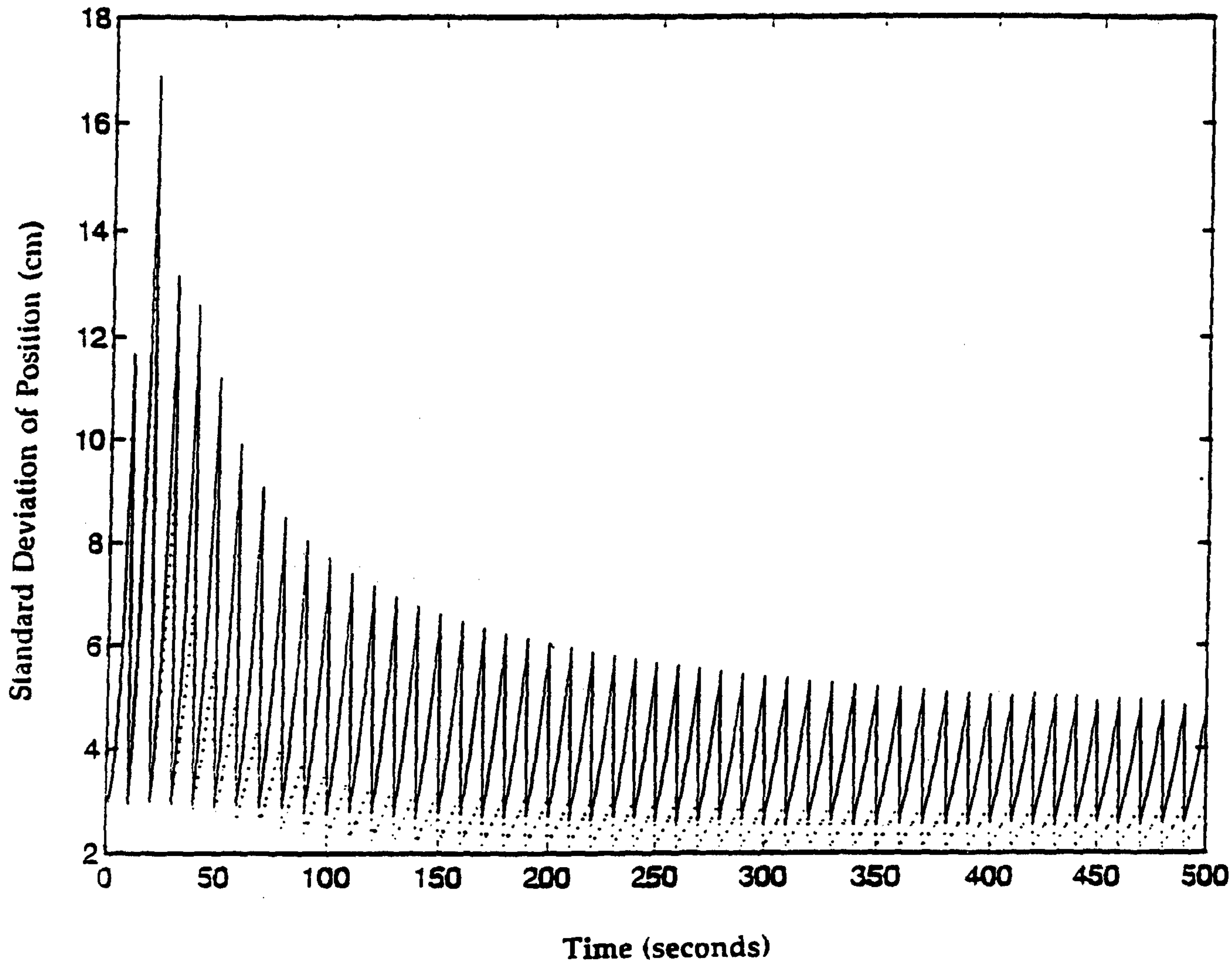

Figure 8 - Position Errors for GPS Outages of 10 Seconds
(East, North and Down Directions)

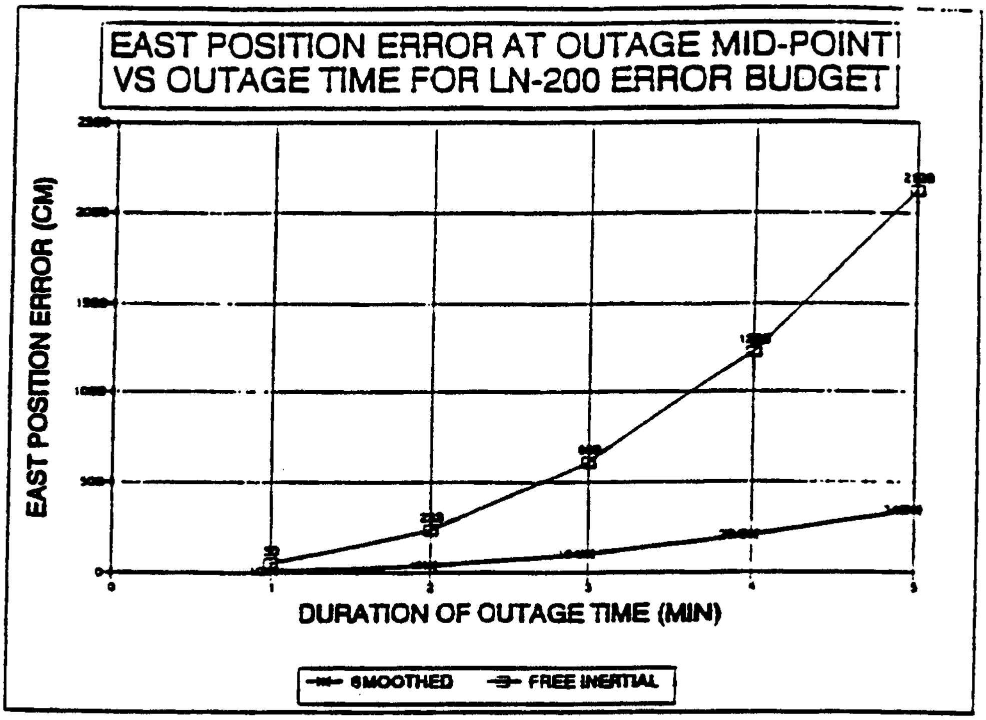

Figure 9 - East Position Error at Outage Mid-Point vs Outage Time for LN-200 Error Budget

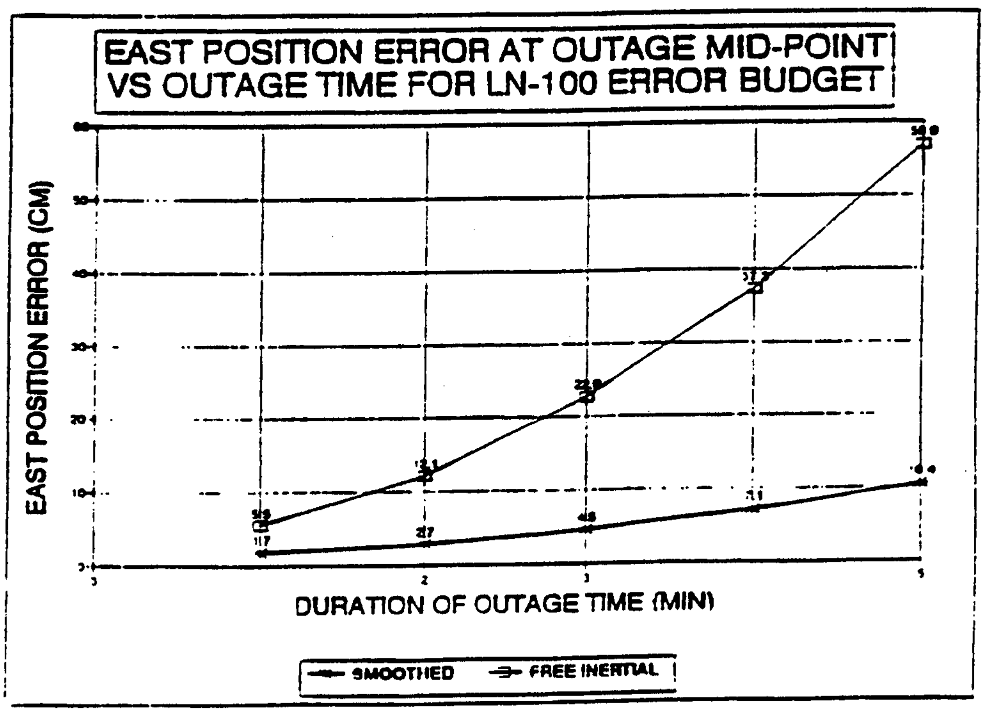

Figure 10 - East Position Error at Outage Mid-Point vs Outage Time for LN-100 Error Budget

5.0 SYSTEM/DESIGN TRADE STUDY PARAMETERS

5.1 Accuracy and Update Rates

The GPR drives the navigation requirements for all of the three platforms (airborne, ground, and man-portable[2]). For all platforms the objective is to produce a data set containing probable UXO locations within a grid of voxels using the raw waveform data.

The radial returns measured from different positions along a survey line may all detect a buried object. These returns will be skewed in time due to the time shift introduced when detecting a buried object from different vantage points on the surface (ground and man-portable platforms) or in the air (airborne platform) which results in a hyperbolic shifting of apparent detection location. Combining multiple-position measured waveforms from the raw data ultimately generates a processed data set, providing net energy return levels at each voxel in the soil, using a process referred to as "focusing". The energy return levels are subsequently processed to produce a map containing the probable UXO site locations.

To perform the focusing of the GPR measurements, it is required to know the location of the platform for all GPR measurements with an accuracy that will allow processing of all the measurements (phases) coherently. The need to know the position for all GPR measurements establishes the navigation rate requirements, and the requirement to process the GPR phases coherently establishes the accuracy requirements as explained below.

Suppose that the radar makes measurements every 5 milliseconds corresponding to 200 Hz rate. The positions of the platform should be known with the same rate. Focusing the raw GPR measurements coherently requires a positional accuracy for each measurement of 1/4 to 1/12 of the smallest wavelength, corresponding to the highest frequency of the transmitted energy. Therefore, for the GPR operating in 50-500 MHz frequencies, the navigation accuracy requirement is between 1/12 (~.05m) and 1/4 (~.15m) of the smallest wavelength (~.60m), corresponding to the 500 MHz frequency. The ~.05m accuracy requirement places a limit on the required rates, since a 200 Hz GPR rate yields a distance between samples of 0.011m (5 x 1600m/3600sec/200 Hz) for a platform moving at 5 miles/hour. Having the positions every 0.011m with an accuracy of .05m does not make any sense, so the navigation rate requirement can be adjusted to 44.44 Hz, which corresponds to .05m platform displacement with a speed of

[1] Only true if the man-portable system uses SAR focusing.

5 miles/hour. Averaging is then used on the waveforms taken within 0.05m spacing, which increases the S/N ratio and the dynamic range. A summary of the data used to determine update rates is given in table 3.

It is evident from the above discussion that the positional accuracy of the moving platform should be between 1/12 and 1/4 of the wavelength corresponding to the highest frequency of the GPR. The navigation rate requirements depend on the GPR measurement rates, the speed of the platform and the provided navigation accuracy. With higher positional accuracies, less GPR averaging will be required, and therefore, potentially more detailed information will be available. The above discussion is valid for time domain, frequency domain (SAR), or hybrid systems, since all of these systems can be thought of as time domain systems through a Fourier transformation.

The position/navigation update rate will correspond to the GPR sampling rate for which the distance between samples is equal to the accuracy of the estimated positions. The GPR samples collected at a higher rate will be averaged.

As mentioned in section 3.2, the commercial dual-frequency GPS receivers available on the market today are providing positions with rates of up to 2 Hz (twice per second). To increase the position rates to the level required for the focusing of the GPR measurements, the GPS system should be integrated with an INS system. This approach will produce the required higher position rates of up to ~90 Hz and will provide navigation during periods when the GPS signals are not available.

Table 3
Data Used to Determine Position/Navigation
Update Rates for Different Platforms

GPR Rate	Platform Velocity	Distance between Samples	Focusing Requirement
	(ground)		
200 Hz	5 miles/hour	0.011m	0.05m
44.44 Hz	5 miles/hour	0.05m	0.05m
	(airborne)		
200 Hz	10 miles/hour	0.022m	0.05m
88.88 Hz	10 miles/hour	0.05m	0.05m
	(man-portable)		
200 Hz	1 mile/hour	0.0022m	0.05m
8.88 Hz	1 mile/hour	0.05m	0.05m

5.2 Interference Between GPS and GPR

Interference between GPS and GPR occurs when the GPR is transmitting in the neighborhood (+/- 10MHz) of its third harmonics, which correspond to the GPS L1 (1575.42 MHz) and L2 (1227.6 MHz) frequencies. This interference is a function of the GPR antenna pattern and its relation to the direction of the observed satellites.

As described in section 5.6, the results of the interference experiments between GPS and GPR conducted at Jefferson Proving Ground in Madison, Indiana, showed that the interference between GPS and GPR made it impossible to achieve cm-level positioning. The GPR system used in these experiments was designed for airborne applications, operating in the frequency domain using a step-chirped transmitter and local oscillator to output pulsed continuous wave (CW) signals between 50 MHz and 700 MHz.

The GPR architecture of the airborne system makes it possible to transmit high power over the specified range of frequencies, and as a result, the S/N ratio of the returned signals is high enough to differentiate them from the background noise. With the high power transmissions of the frequency domain airborne systems, interference with GPS is more likely as compared to the lower power transmissions of the time domain systems employed for the ground and man-portable systems.

5.3 Environmental Factors

The GPS satellites transmit spread-spectrum signals consisting of two components: Link 1 (L1), at a center frequency of 1575.42 MHz; and Link 2 (L2), at a center frequency of 1227.6 MHz. These signals can be obstructed by thick foliage, buildings, etc. As a result, GPS navigation may not be possible close to high trees with thick foliage, close to high buildings, or close to other obstructions. This will affect both the ground and man-portable platforms.

Since many UXO sites contain high trees it is likely that in many cases GPS navigation will not be possible. In these cases an INS which is integrated with the GPS system will provide the navigation for the ground and man-portable platforms.

The errors affecting the INS positions grow as the integral in time of the accelerometer, gyroscope, initial tilt, and heading errors (section 4.2). As a result, if GPS positions are not available for a certain period of time the INS position errors will grow beyond the level required for successful processing of the GPR measurements. In these cases the ground and man-portable platforms need to come to a complete stop and perform Zero Velocity Updates (ZUPs) to correct the INS navigation errors.

The time interval between ZUPs depends on the required positioning accuracy, the quality of the INS, and the length of time during which GPS positions are not available. For instance, to achieve positioning accuracies of .05m or less with a LN- 100 INS system, and without any GPS updates, the interval between ZUPs should not be more than 3 minutes (figure 10).

For an airborne platform, if the antenna is properly positioned, obstructions are not a problem during regular operating sessions. However, in an airborne environment, electromagnetic radiation may interfere with the weaker L2 GPS signal, which may cause interruption of the high accuracy positioning (section 5.6).

5.4 Tropospheric Delay

The delay experienced by radio waves when propagating through the electrically neutral atmosphere is called tropospheric delay. This propagation delay is generally split into two components, called hydrostatic (or dry), and wet, each of which can be described as a product of the delay at zenith and a mapping function, which models the elevation dependence of the propagation delay. This modeling is very accurate (~0.01-0.02m) for ground stations.

When operating in an airborne environment the model must accurately represent the relative tropospheric delay caused by this altitude difference. The troposphere extends from the ground up to an average of 11 kilometers. The troposphere within a few kilometers from the ground is considered to be the boundary layer. The boundary layer profile is affected by wind, evaporation, heat transfer, pollutant emissions and terrain-induced flow modification. The boundary layer thickness changes in time and space from a hundred meters to a few kilometers. As the ground warms and cools, the boundary layer profile changes, which in turn changes the temperature and humidity gradient with altitude. Thunderstorms can also modify the boundary layer within minutes. These and other effects reduce significantly the accuracy of the tropospheric models making it very difficult to perform high accuracy (~.05m) level positioning. Therefore, for the airborne platforms the weather conditions play a very important role in high accuracy positioning. Experiments should be conducted to establish the weather conditions that will allow high accuracy positioning when surveying with an airborne platform.

5.5 Temperature, Shock and Vibration

Temperature, shock and vibration have different values and different behaviors for the airborne, ground, and man-portable platforms. The recommended LN-100 and LN-200 Inertial Measurement Units (IMUs) have been tested for low and high temperatures and for different shock and vibration parameters. Table 4 shows the environmental operation parameters for the LN-100 and LN-200 IMUs.

Table 4
Environmental Characteristics
of LN-100 and LN-200

	LN-100	LN-200
Temperature	-54 C to +71 C	-54 C to +85 C
Vibration (random)	17.4 grms endurance	17.9 grms endurance
	8.1 grms performance	11.9 grms performance
Shock	21g /25Hz	4.2g/100HZ to 1186g/1500Hz

Both the LN-100 and the LN-200 IMUs have been built for the Department of Defense and have been tested for airborne rotary Wing, Uninhabited Fighter, and Uninhabited Transport environment. For the airborne platform (helicopter) the random vibration is in the order of 2.5 to 3 grms, and under moderate turbulence the shock is in the order of 5g over frequencies of 10 to 40 Hz. The temperature range for the airborne environment is well within the operational characteristics of both the LN-100 and LN-200 IMUs.

The recommended Allen Osborne and SSE dual-frequency GPS receivers have been tested for low and high temperatures and for shocks and varying frequencies. Table 5 shows the environmental operational parameters for the Trimble SSE and the Allen Osborne Turbo-Rogue GPS receivers.

In the ground platform environment the shock and vibration characteristics are very different than those in the airborne environment. However, the shock and vibration operational range of both the INS and GPS instruments is very wide, and therefore, it is not anticipated to have any problems in navigation, especially when shock and vibration mounting is used.

Table 5
Environmental Characteristics for GPS Receivers

		Turbo-Rogue	Trimble SSE
Temperature	(Antenna)	-40C to +70C	-40C to +75C
	(Receiver)	-20C to +50C	-20C to +55C

5.6 Results and Recommendations

Results and recommendations for the different platforms are presented separately. As part of the conceptual design for the Airborne Navigation System, the results of experiments to test interference between GPS and the GPR at Jefferson Proving Ground, have been included.

5.6.1 Conceptual Design of the Airborne Navigation System

The airborne system consists of two components (figure 11); the base and the airborne components. The base component consists of one computer, one dual-frequency GPS receiver, and a radio receiver/transmitter, all of which are enclosed in a waterproof container for continuous use in outdoor exposed environments. The base component contains a power amplifier which allows operation of the system over distances of up to 20 miles. The airborne component consists also of one computer, one dual-frequency GPS receiver integrated with an INS, and a radio receiver with an antenna. The base station provides the differential signals for high accuracy differential GPS positioning. Appendix C lists the recommended hardware for the different platforms.

The base and airborne GPS observations will be processed together with the INS measurements by the airborne computer to estimate the positions of the airborne platform. These positions are used to focus the GPR measurements in near real-time (~1 minute delay). The results of the focusing will be shown on the airborne computer display to allow the operator to calibrate the GPR operating parameters.

As explained above, the required accuracy to process the GPR data coherently is 1/12 (~.05m) of the wavelength (~.60m) corresponding to the highest operating frequency (~500 MHz) of the GPR system in use. Flying a helicopter with a speed of 10 miles/hour and taking radar measurements every 5 milliseconds results in a rate of 200 Hz (200 Hz=1/0.005 sec) with a displacement of the airborne platform 0.022m on the ground. However, with an accuracy of 0.05m the maximum rate that can be used is 88.88 Hz (88.88 Hz=200 Hz x 0.022m/0.05m) which is easy to obtain with an INS system.

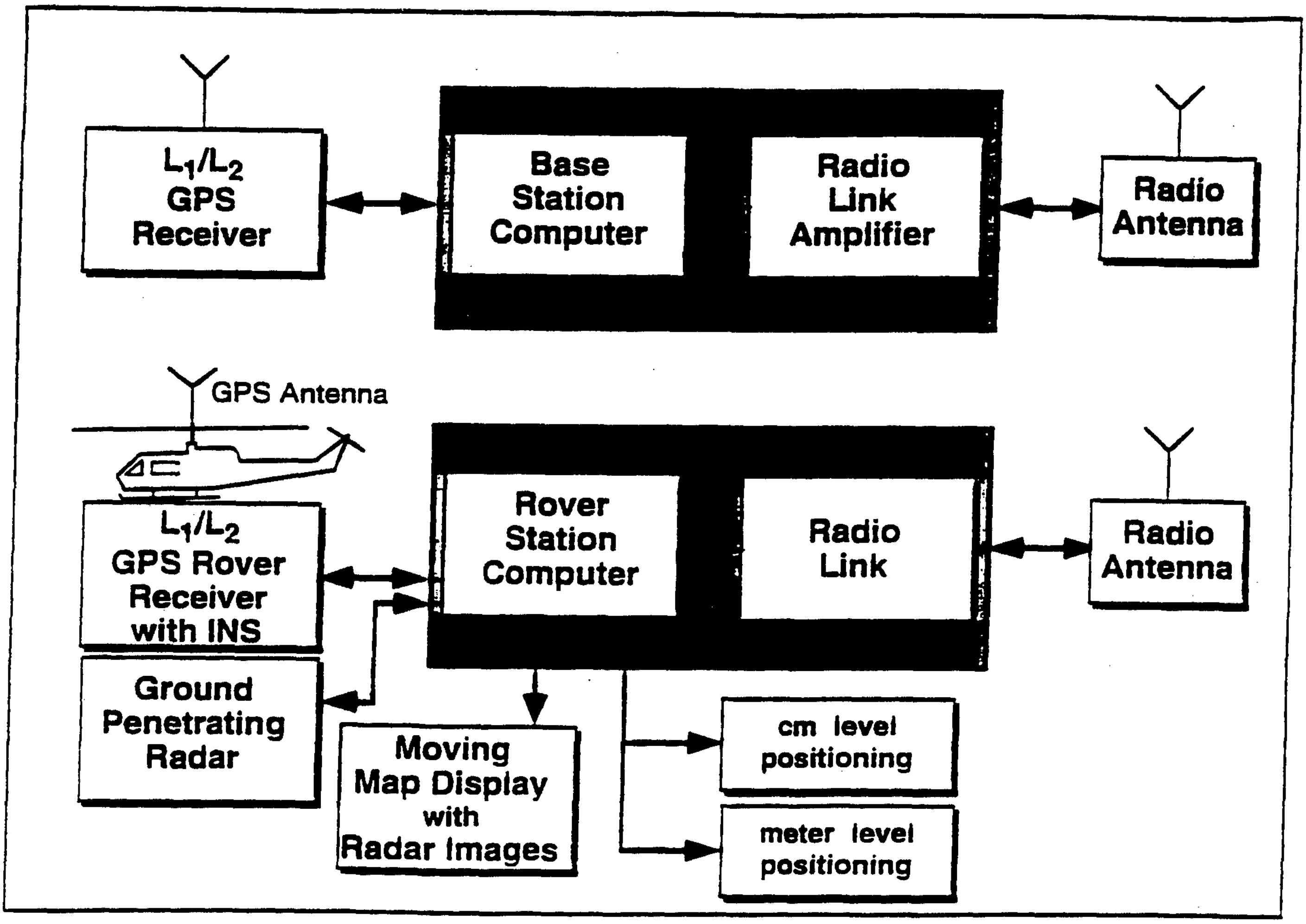

Figure 11 - Airborne Based Real-Time cm-level GPS Positioning System

Flying along a predefined survey line with a helicopter and the GPS antenna properly positioned, the GPS satellite signals will not be obstructed, assuming that electromagnetic interference from the GPR system or other sources will not cause any disruption of the GPS signal reception. Under these conditions the basic role of the INS system for the airborne platform will be to provide the higher position rates necessary to focus the GPR phase measurements. Without any obstruction and with GPS update rates of 1-2 Hz, the low cost LN-200 IMU is capable of providing the high positioning rates and the accuracy required for the focusing of the radar phase measurements.

Described below are the results of the GPS/GPR interference experiments at Jefferson Proving Ground in Madison, Indiana. From these results it is evident that a critical issue for the airborne platform is the location of the GPS antenna relative to the GPR antenna. The antenna for the airborne platform should be located on a place which minimizes interference between GPS and GPR as well as between GPS and other sources of electromagnetic radiation, and where the GPS satellite signals are not obstructed. One possible position of the antenna is to locate it above the main rotors. This position provides the most stable position as far as the airborne induced motion/vibration of the antenna itself is concerned. The following voice communication radio frequencies have harmonics in the main commercial GPS band of 1.57542 GHz are known to cause interference, and should be avoided: 121.050, 121.175, 121.2, 131.275, and 131.3 MHz.

The mounting of the antenna above the main rotor will be an expensive undertaking. The equipment mounted above the main rotor on attack helicopters can provide an approach to mounting as well as an estimate of the cost. Any other location which minimizes interference with the GPR antenna and allows tracking of all of the visible satellites will be a good location since the orientation provided by the INS will allow the transformation between the GPS and the GPR antenna phase centers. It is recommended to study the helicopter's electromagnetic interference to find a location for the GPS antenna, other than above the main rotor, which can satisfactorily receive both L1 and L2 signals. An alternate location should result in a less expensive installation.

As mentioned in the previous section, changes of the boundary atmospheric layer may reduce significantly the effects of the tropospheric models, making it very difficult or even impossible to perform high accuracy GPS positioning of the airborne platform. It is recommended to conduct experiments and establish the weather conditions that will allow high accuracy positioning of the airborne platform.

The IMU LN-200 has been tested for a variety of airborne environments for shock and vibration. Its operational temperature range is very wide and, therefore, it is not anticipated to have any operational problems coming from shock, vibration, and temperature changes. As for the GPS receivers, several airborne experiments using Trimble SSE or Turbo-Rogue receivers have been conducted. The ability to track the GPS satellites signals without any problems arising from shock, vibration or temperature changes, as long as the receiver was mounted rigidly inside the aircraft.

Interference between the GPR and GPS at Jefferson Proving Ground, Madison, Indiana, Sep 94

Differential GPS data was collected at a 1 Hz rate, as the vehicle on which the GPR was mounted was moving at approximately 0.27 feet/second. This data was processed using CFM GPS software to determine the vehicle's motion. The requirement is for ~0.07m positioning of the GPR in quasi real-time. The data discussed here is for the last 3.5 hour period on September 29, 1994.

The GPS satellites transmit signals at two frequencies, L1 and L2. Very accurate (cm-level) differential positioning can be achieved with only a few epochs of data using double difference widelane observables (L1-L2) derived from the L1 and L2 carrier phase observations for epochs when 4 or more satellites are available. The GPS receiver tracks the L1 signal more easily than the lower power L2 signal. If only L1 data is available, it is more difficult and takes longer (5 to 15 minutes) to determine the carrier phase ambiguities required for very accurate differential processing.

Figure 12 shows the motion of the satellites during the time of the experiment. The concentric circles represent the constant elevations, 0, 30, 60 and 90 degrees, and the azimuth is indicated circularly about the center of the graph. Only satellites with an elevation >5 degrees are indicated on this graph as those with elevations <5 degrees are excluded from the processing. The signals from low elevation satellites have relatively large errors as the signals travel longer distances through the troposphere and ionosphere. From figure 12 it can be seen that, at any time during the experiment, 6 to 8 satellites have elevations >30 degrees. This number of satellites is sufficient to achieve high accuracy (cm-level) differential GPS positioning. The quality of the GPS data collected during this experiment was unexpectedly poor. For a large number of the epochs throughout the duration of the experiment the L2 data and, in many cases, even the L1 data is missing. For many epochs, even though 6-8 satellites are available, less than 4 have L2 data and the accurate widelane processing cannot be performed. The data was processed on the basis of the L1 data, as described below.

Date: 1994/ 9/20

Location: Jefferson Proving Ground

Lat: 38:52:46.30 N   Lon: 85:22:33.00 W

Time Zone: Greenwich Std Time

Local Time - GMT = -0.00   Mask: .05 (deg)

>>> Satellite Sky Plot <<<

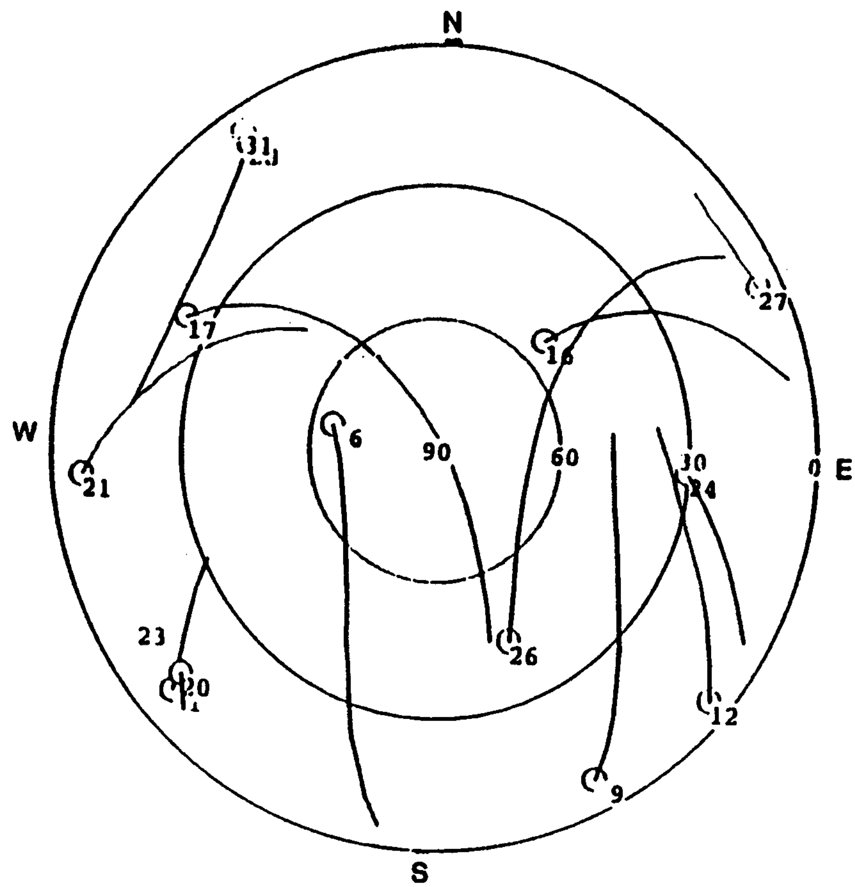

Figure 12 - GPS Satellite Trajectories

Figures 13 and 14 show the variation in the Position Dilution of Precision (PDOP) during the time of the experiment. The PDOP relates to the geometry of the satellites and varies in a regular fashion as this geometry changes. Figure 13 shows the expected PDOP calculated from the satellite orbits. Figure 14 shows the PDOP calculated from the satellites used in the processing, i.e., those satellites for which L1 data is available. The spikes in figure 14 occur when satellites are missing L1 data and the geometry of the satellites used in the processing has been altered. The spikes in the PDOP correspond to sudden accuracy degradation of the estimated velocities and positions as is seen by comparing figure 14 with figures 15, 16, and 17.

Figures 15, 16, and 17 show the change in position (velocity) between consecutive epochs for the east, north and up directions. For a large number of epochs the velocities appear as pairs of clipped vertical lines in the plots. At these times the geometry is either very poor or L1 data is available for less than 4 satellites, in which case velocities are not computed.

During the experiments the vehicle was remotely controlled, moving with a uniform speed of 0.27 feet/second in approximately the north-south direction. Comparing the velocities in figures 15, 16 and 17 with the PDOP in figure 14, it is evident that the velocities are incorrect by a large factor when there is a spike in the PDOP. So, low accuracy estimates of velocity are removed by rejecting velocities for which the PDOP is >2.5. The velocity for these epochs and for the epochs with less than four satellites being tracked have been estimated through linear interpolation. The results of the interpolation are shown in figures 18, 19, and 20. In these plots, the velocity measurements are much less noisy.

It is evident from these figures that even the cut-off PDOP value of 2.5 did not eliminate the non-uniform behavior of the estimated velocities. This is the result of the discontinuities in satellite tracking caused by the operation of the radar. These discontinuities will introduce systematic errors in the estimation of the position through the integration of the velocities. Although this method is very sensitive to the accumulation of systematic errors, it was used to estimate the positions because this is the only method that can produce accurate positioning with so many interruptions of the GPS satellite tracking.

The corresponding distances covered by the vehicle in the east, north and up directions, derived by integrating the velocities in the corresponding directions, were plotted in figures 21, 22, and 23. These show the general motion of the vehicle from its initial stationary position. The time at which the motion starts can be seen as the time at which the distance changes and at which

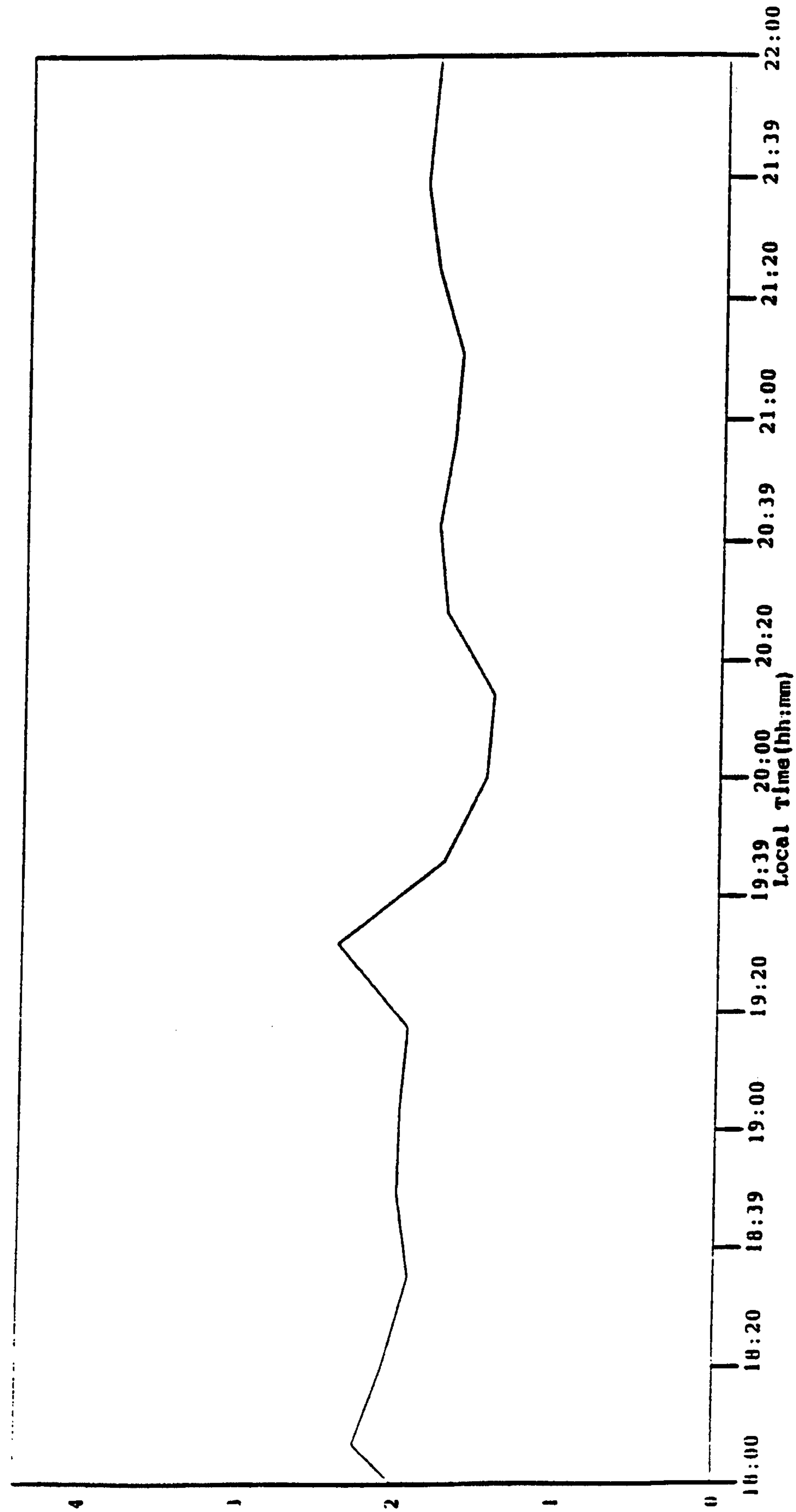

Figure 13 - PDOP for GPS Satellites

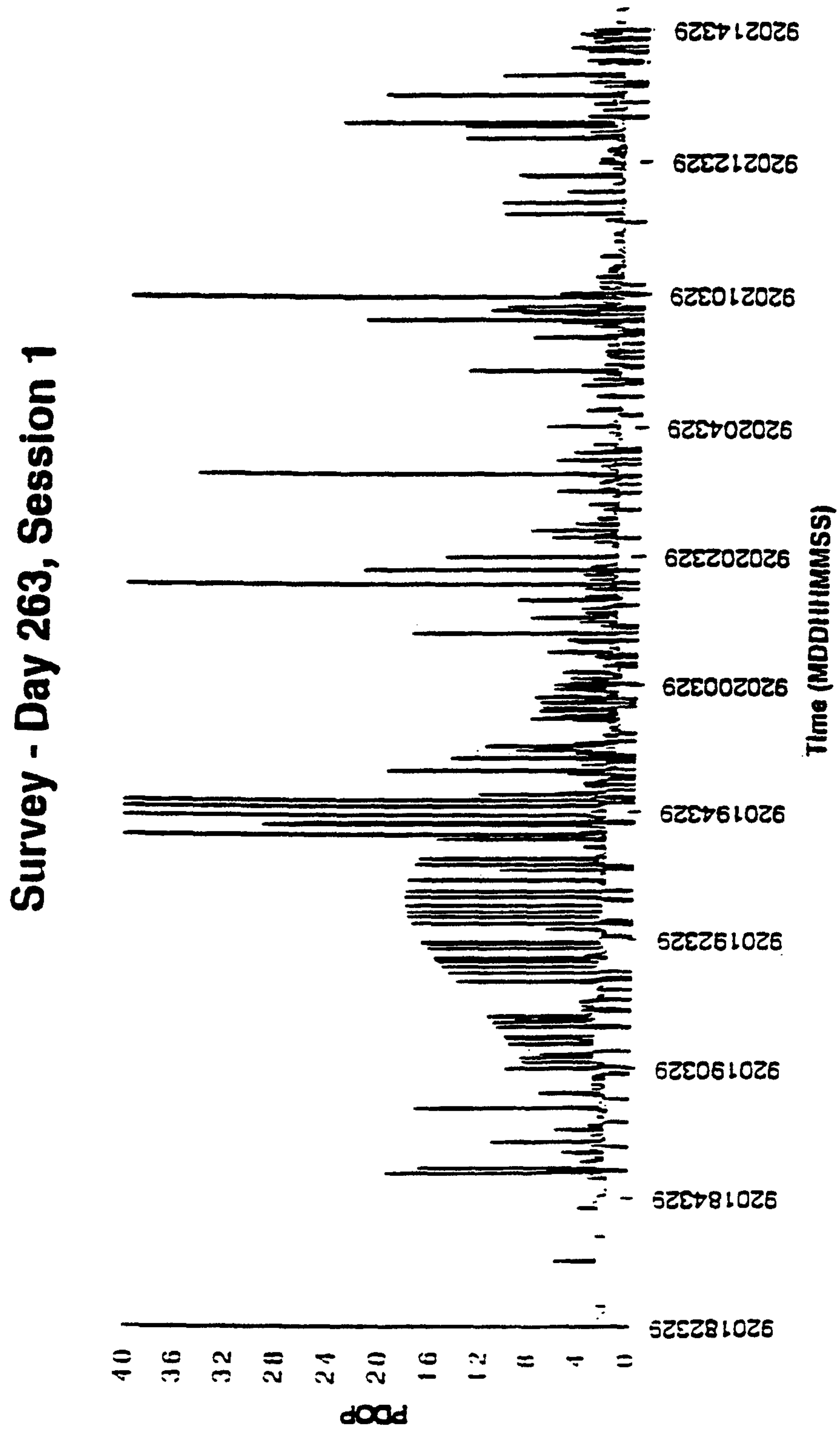

Figure 14 - PDOP for GPS Satellites with L1 Data

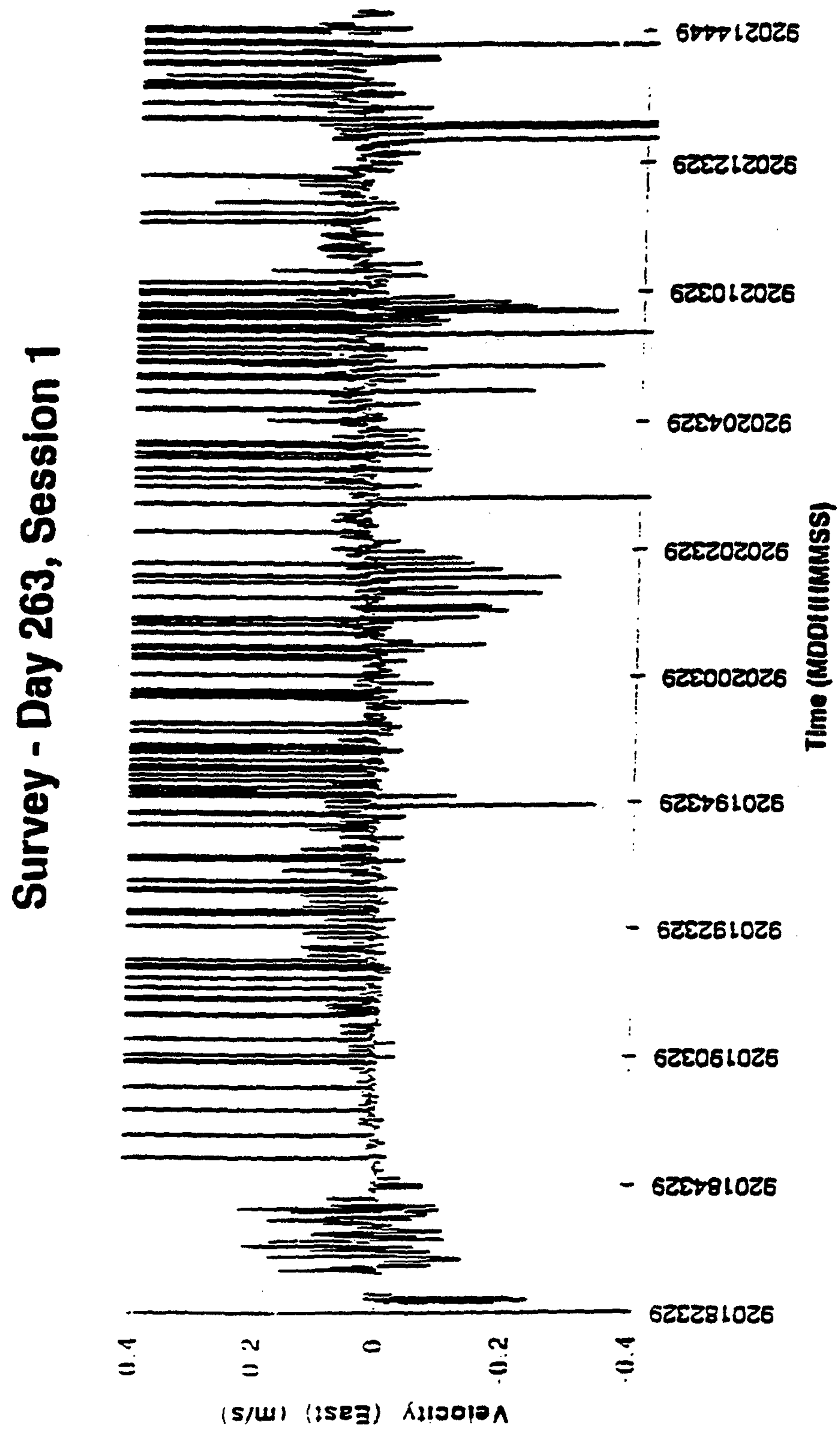

Figure 15 - Velocity (East)

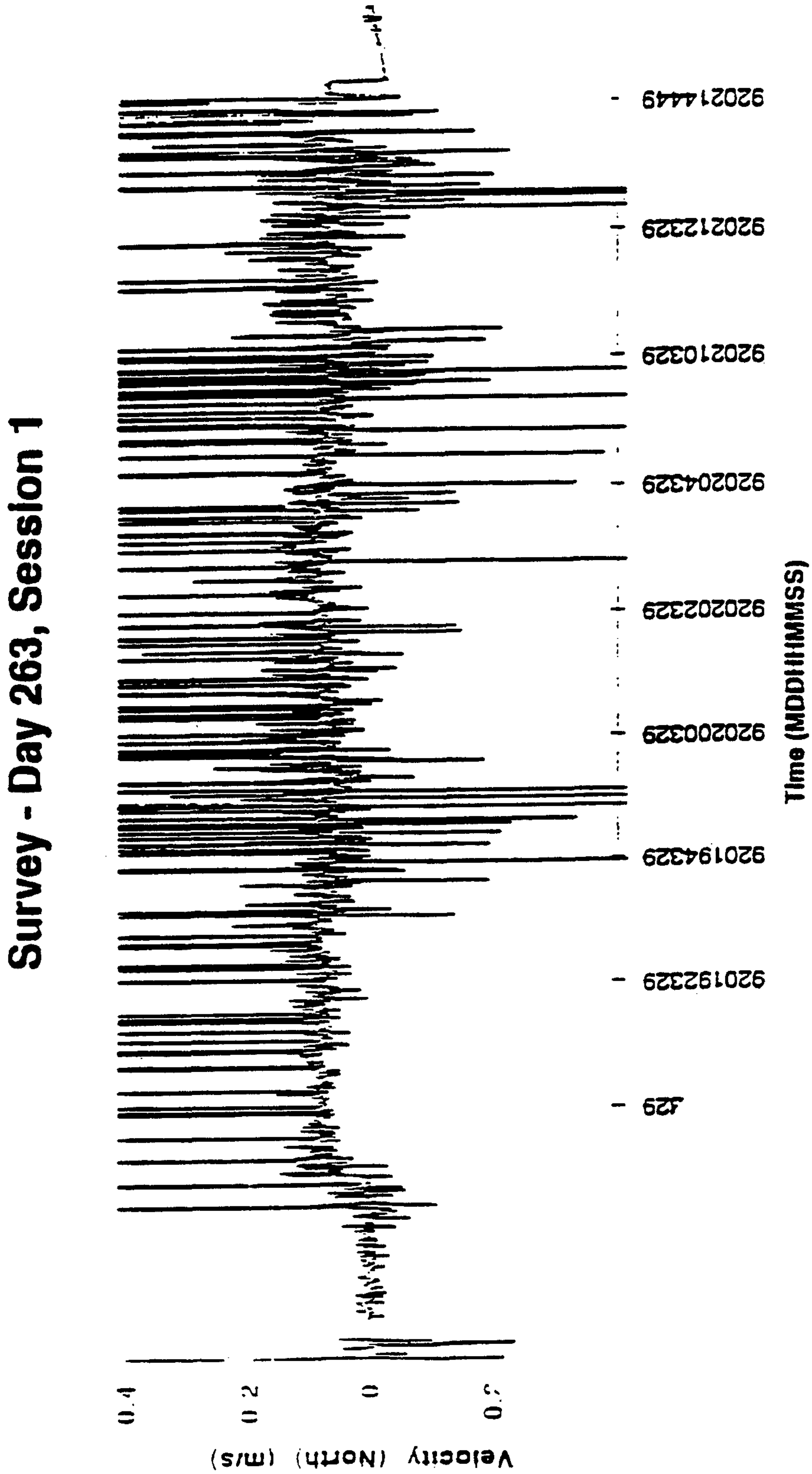

Figure 16 - Velocity (North)

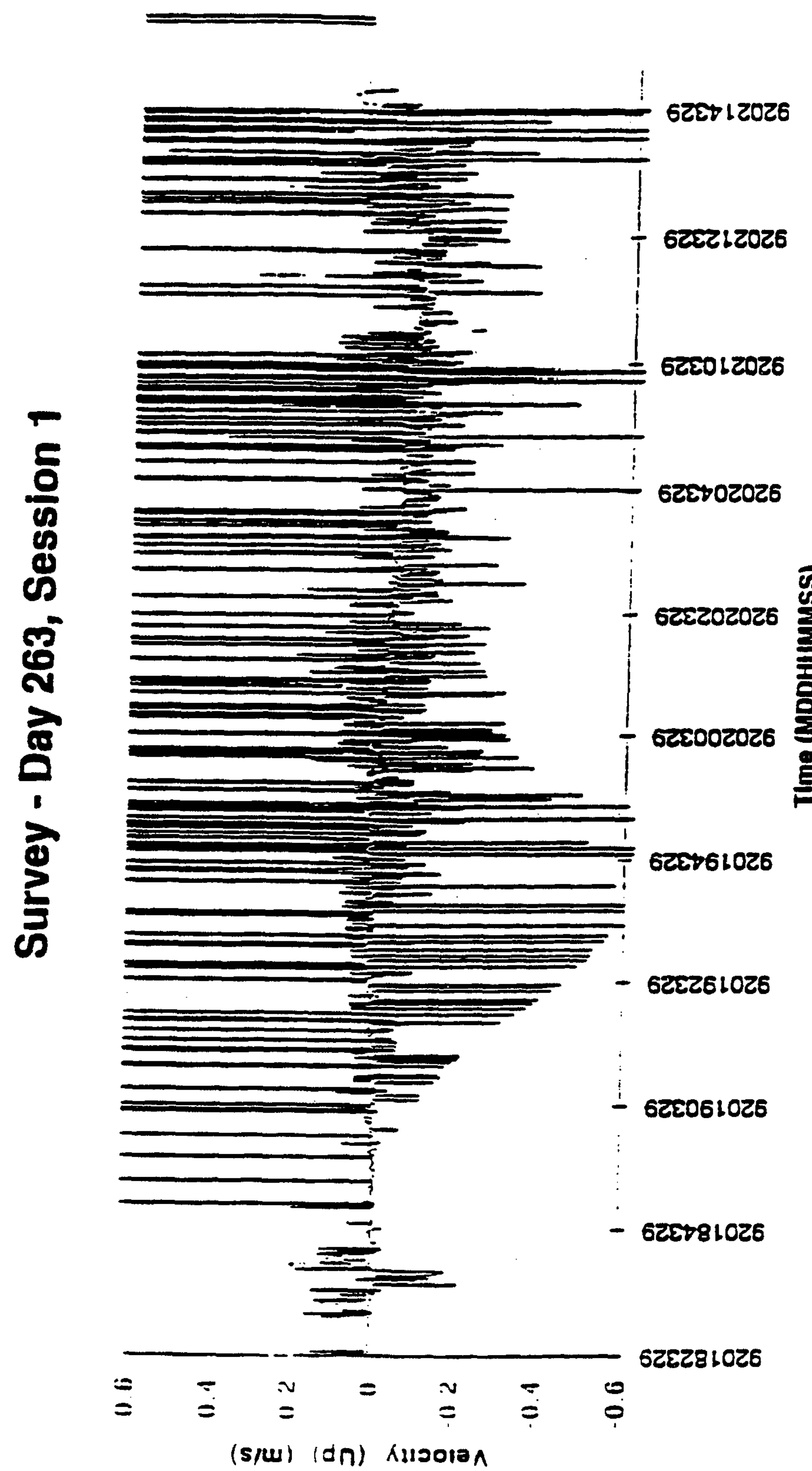

Figure 17 - Velocity (Up)

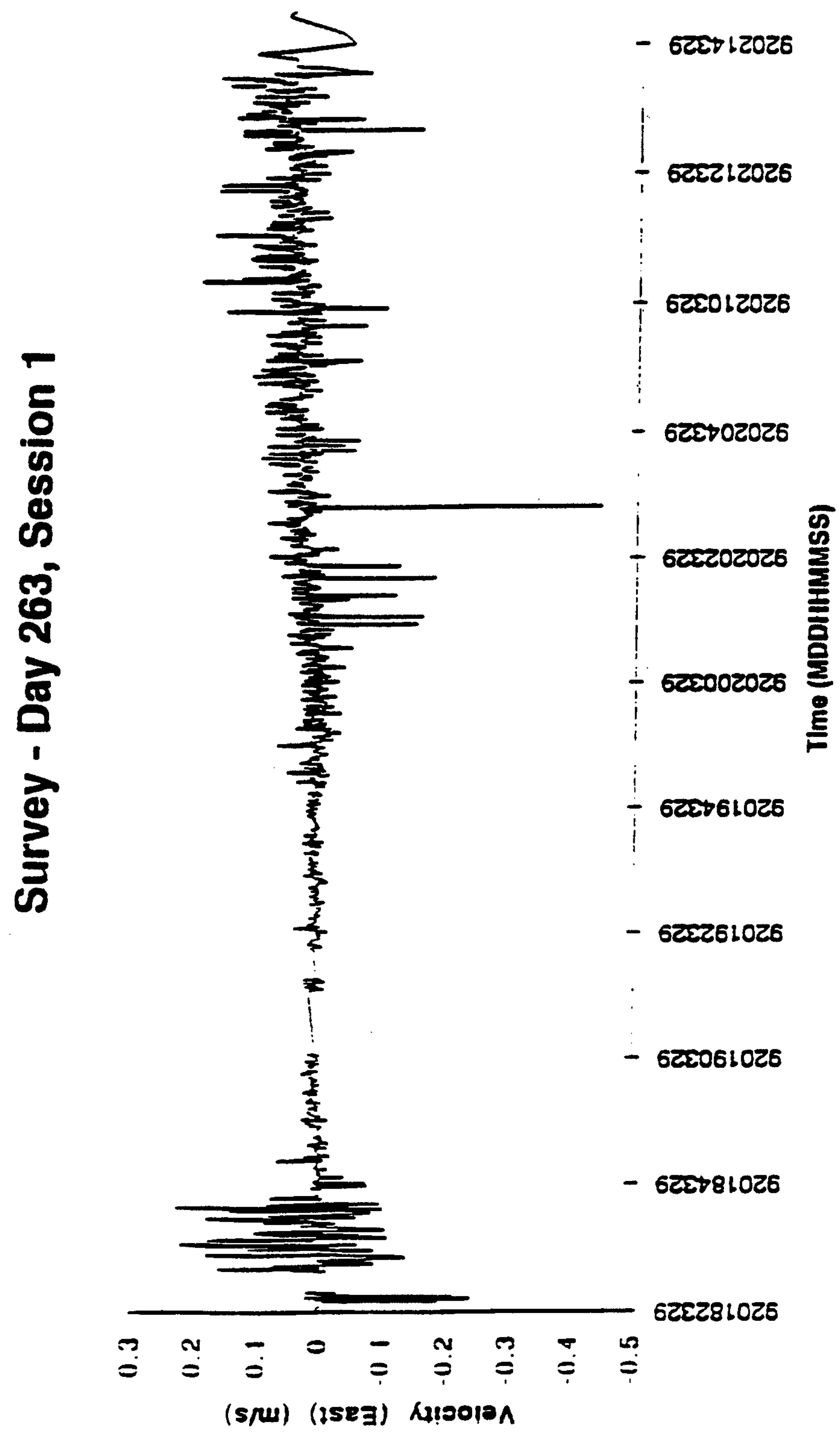

Figure 18 - Velocity (East) - Interpolated

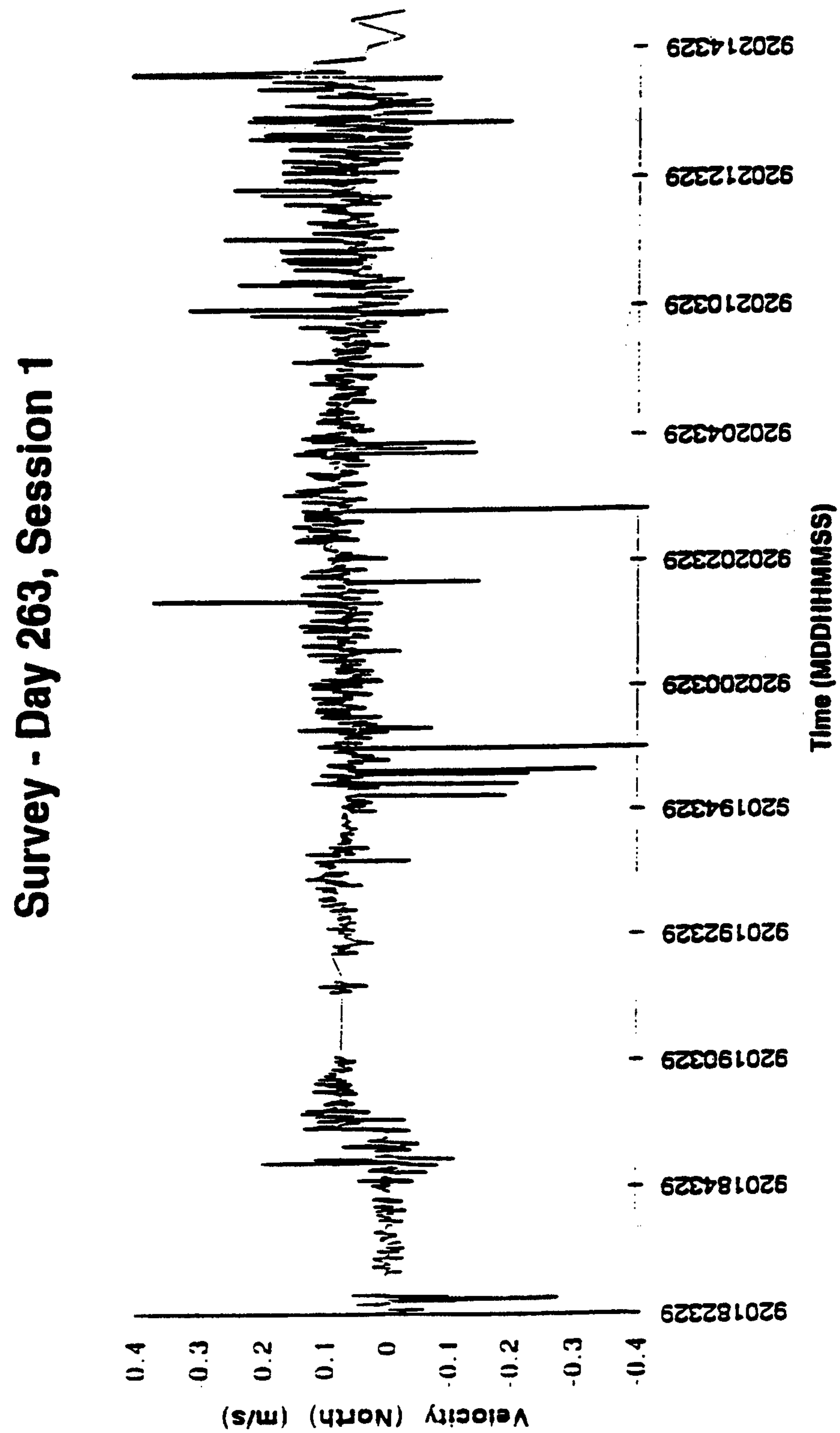

Figure 19 - Velocity (North) - Interpolated

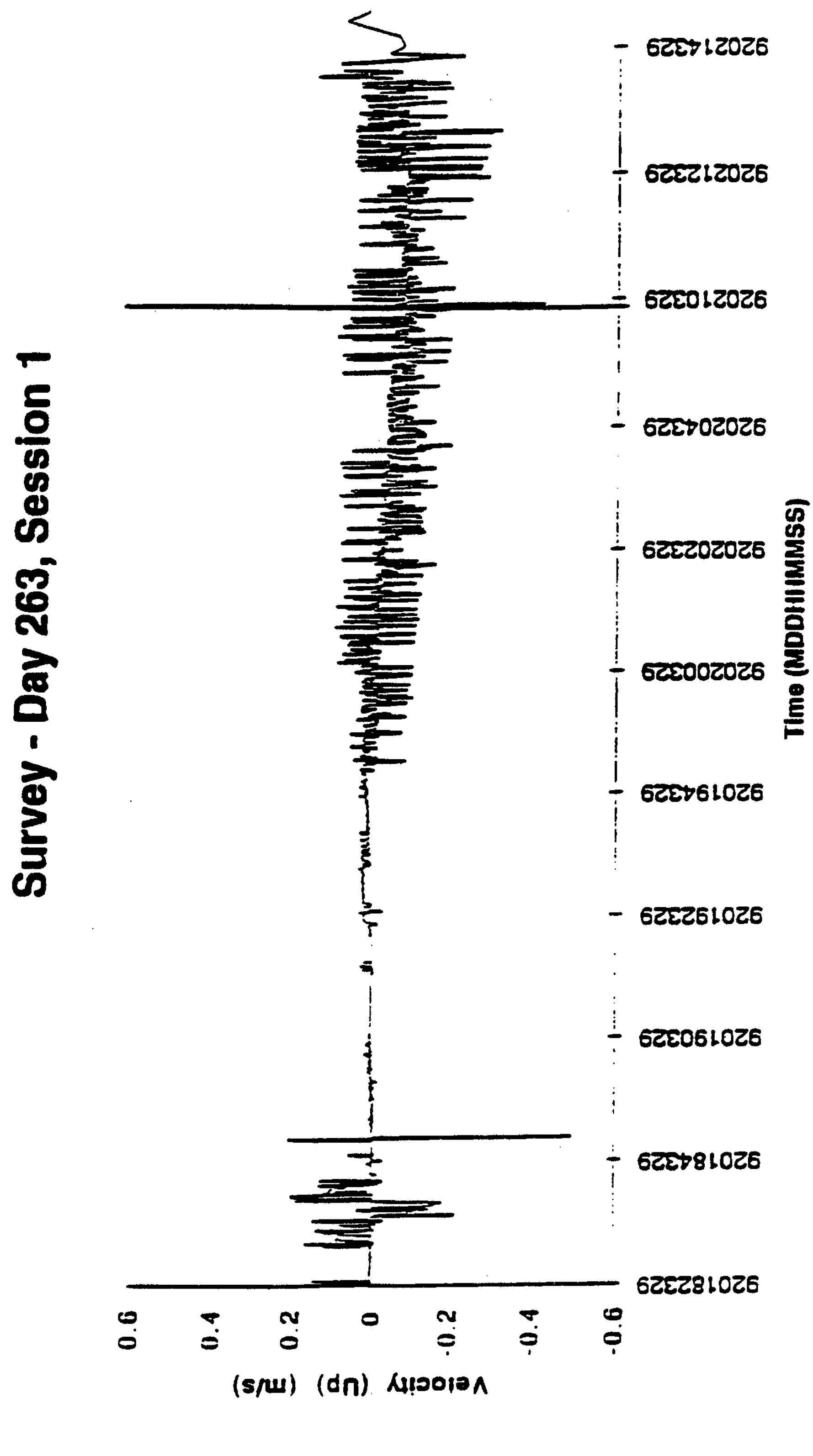

Figure 20 - Velocity (Up) - Interpolated

the velocity in the north direction (figure 19) changes. The interruption of the L1 signal is caused by interference with the signal from the GPR. Interference between GPS and GPR occurs when the GPR is transmitting in the neighborhood (+/-10 MHz) of its third harmonics corresponding to the L1 and L2 GPS frequencies. This interference is dependent on the GPR antenna pattern in relation to the GPS signal and can interfere with signals from high elevation satellites, for which the GPS data should otherwise be of good quality. The GPR was transmitting in the east-west direction and, examining the GPS data from the receiver mounted with the GPR data, satellites 16 and 17 moving from west to east (see figure 12) lose their L1 and L2 data very often. In fact, over the duration of the experiment none of the satellites were tracked continuously.

The plots in figures 18 through 23 show that the velocity and the corresponding distance can be determined despite the noise in the data. However, due to systematic errors introduced from the sudden changes of PDOP, this method of integrating the estimated velocities is not adequate to provide high accuracy results. It is recommended therefore, that for high accuracy positioning, the airborne GPR be equipped with filters to eliminate the interfering frequencies. It is also recommended to perform similar GPS/GPR interference experiments for the ground and man-portable platforms.

5.6.2 Conceptual Design of the Ground Vehicular Navigation System

The ground GPS navigation system is very similar to the airborne system. A block diagram of the real-time cm-level GPS/INS positioning system is shown in figure 24. This system consists of two units; the base and the rover units. The base unit consists of one computer, one dual-frequency GPS receiver, one radio receiver/transmitter, and a power amplifier, all of which are enclosed inside a waterproof enclosure for continuous operation in outdoor, exposed environments. The power amplifier is used to operate the system over distances of 20 miles. Without an amplifier, the system can operate over distances of 5 to 10 miles. For most of the UXO sites, the operating distance is less than 10 miles, and therefore, a power amplifier will not be needed for the base unit.

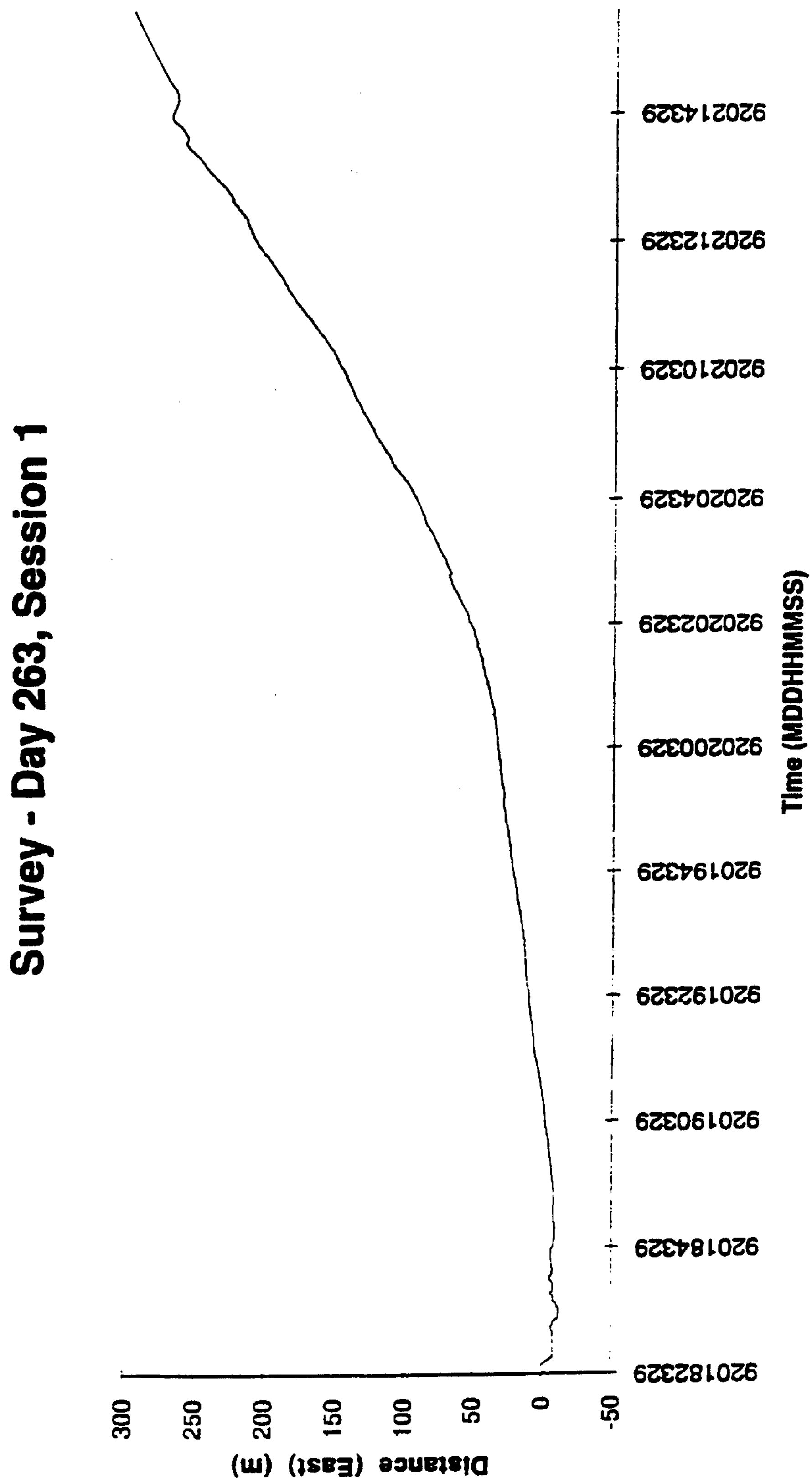

Figure 21 - Distance (East)

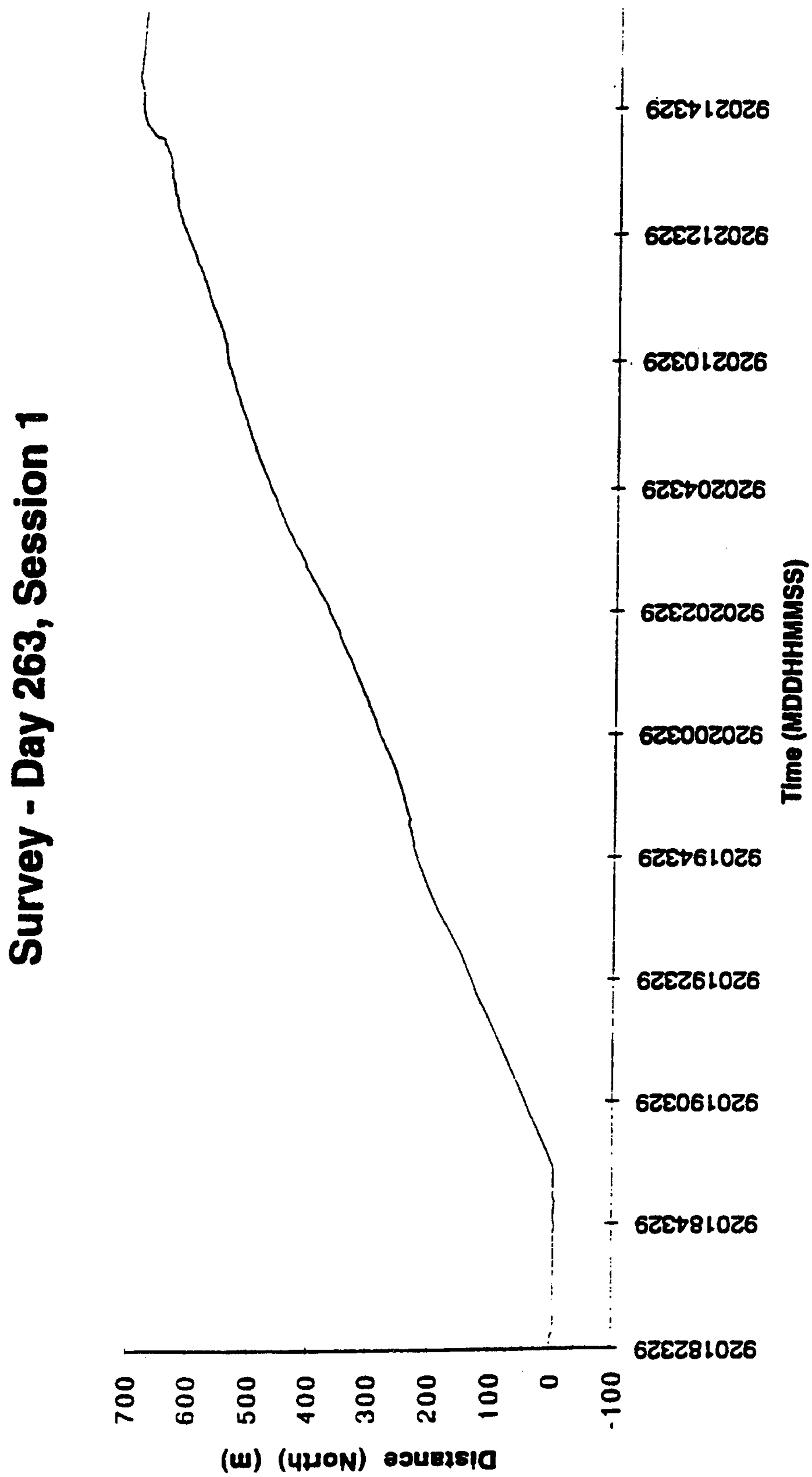

Figure 22 - Distance (North)

Figure 23 - Distance (Up)

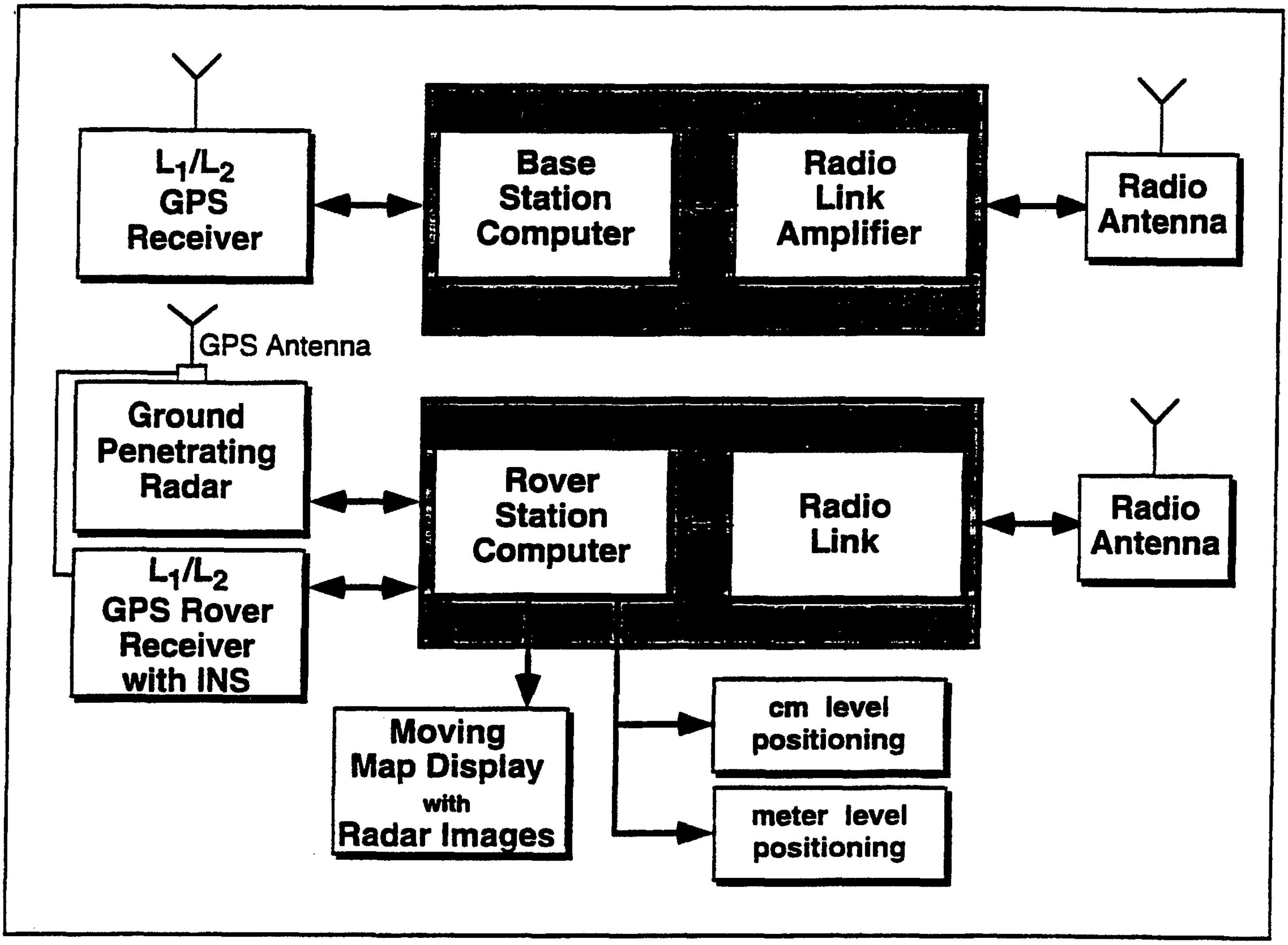

Figure 24 - Ground Based Real-Time cm-level GPS Positioning System

The rover unit consists of one computer, one dual-frequency GPS receiver integrated with an IMU and a radio receiver. The base station provides the differential GPS observations for real-time and post-processing cm-level positioning. The radio transmitter of the base unit transmits the differential observations to the rover unit for real-time cm-level GPS positioning. The real-time cm-level positioning is used at the Rover Station (ground platform; Subsurface Ordnance Characterization System) to focus the GPR phases in near real-time for the calibration of the GPR parameters.

The required accuracy to focus the GPR data coherently is 1/12 of the wavelength corresponding to the highest frequency. With the highest frequency of 500 MHz (~0.60m), the required positioning accuracy for focusing the GPR data is 0.05m (1/12 x 0.60m). Assuming that the ground-vehicle platform moves with a speed of 5 miles/hour and that the GPR makes measurements every 5 milliseconds (200 Hz), the distance on the ground between subsequent GPR measurements is 0.01111m. Since the required accuracy is only 0.05m, the GPR measurements should be averaged in time so that the time interval between subsequent radar measurements corresponds to a displacement of 0.05m on the ground. The time interval required to move 0.05m with a speed of 5 miles/hour is 22.5 milliseconds corresponding to a rate of 44.44 Hz. Therefore, the highest rate that can be used is 44.44 Hz. With higher navigation accuracies, less averaging will be required for the radar measurements. Less averaging of the raw radar measurements may potentially allow more efficient focusing, because the required averaging will be determined and it will take place at the digital image processing stage when the buried objects are identified.

Interference between GPS and GPR for the ground platform is possible and can be detrimental to high accuracy navigation. The experiment presented in section 5.6.1 were performed using a frequency domain (step-chirped) system with high transmitting power (~1 Watt). The ground-vehicle GPR will be a time-domain system with an output power substantially lower than the output power of the frequency domain airborne GPR system. With lower power, it is possible that the ground GPR system will not interfere with the GPS satellite signals. It is recommended, therefore, to conduct interference experiments between GPS and GPR using the exact GPR system that will be used for the ground platform. In the ground platform environment, it is very likely that for certain periods of time, the GPS signals will be obstructed by high trees with thick foliage. For proper focusing of the GPR phase data, it is important to navigate with high accuracy (~.05m) during these periods of time. This can only be achieved by integrating GPS with a high accuracy IMU able to maintain cm-level accuracy for several minutes. From figures 9 and 10 it is evident that the LN-100 IMU is able to deliver .05m - 0.10m accuracy in smoothing mode for 3 to 5 minutes without any GPS updates. As seen in figure 10, the accuracy of the IMU is much worse in free-inertial mode than the accuracy obtained in smoothing mode. For the focusing of the GPR data the navigation solution will be based on the smoothing mode because the position of the ground-platform is needed either in near real time (~1-2 minutes delay) for the focusing and calibration of the GPR or in post-processing for the final focusing of the GPR phase measurements. If the GPS signals are obstructed for longer periods, then the ground platform should come to a complete stop and perform a ZUP.

For the ground platform, the integration of the GPS with an IMU should be performed at the measurement level (tight), rather than at the position level (loose). Integrating GPS with IMU at the measurement level makes it possible to correct the IMU errors using measurements even during periods when less than four satellites are visible. Integrating GPS with an IMU at the position level (loose integration) assumes that GPS positions are available, which requires measurements from at least four satellites. In the ground platform environment, however, there will be many times when less than four satellites will be visible due to obstructions. During these times, it will be necessary to correct the INS, which necessitates integration of GPS with the IMU at the measurement level. With less than 4 satellites visible, ZUPs will be required when the time interval between the GPS updates is longer than 5 minutes. This time interval will depend on the strength of the GPS satellite measurements.

Another important issue is the type and the location of GPS antenna on the ground platform. The Simultaneous Data Collection and Processing System (SIDCAPS) on the ground platform will be equipped with an array of sensors, including the GPR and magnetometers positioned on a trailer that is towed around the designated site. The optimum position of the GPS antenna and the INS is on the sensor trailer and not on the tow vehicle. The GPS antenna should be positioned anywhere on the trailer above any trailer obstructions, where the GPR interference is minimum. The GPS antenna should be of geodetic type (i.e., equipped with a ground plane) to minimize the effect of multipath (i.e., reflected satellite signals) originated at the sensor trailer or the tow vehicle. Having an IMU and the GPS antenna on the sensor trailer makes it possible to transfer the GPS antenna phase center to the GPR antenna phase center using the orientation parameters provided by the IMU. If the IMU and/or the GPS antenna are located on the tow vehicle, then additional sensors (i.e., linear or rotary sensors) must be provided to measure the relative orientation of the tow vehicle and the sensor trailer. This implementation will make the system more complicated and more expensive.

It is recommended that the GPR/GPS/IMU be developed as a separate unit that will provide the GPR/GPS/IMU data to the control computer located on the tow vehicle. The control computer will display the current position of the GPR antenna on a moving map display (section 6), and it will perform the near real-time focusing of the GPR phase data for calibration of the operational GPR parameters. The control computer will receive the base station differential GPS data, and it will combine the GPS data from both GPS receivers with the IMU data to compute high accuracy positions of the GPR antenna phase center.

Another alternative is to have a computer as part of the GPR/GPS/IMU system. This computer will receive the differential GPS data from the base station, and it will combine the GPS data from base and rover GPS receivers with the IMU data to compute real-time high accuracy positions for the GPR antenna phase center. It will perform the near real-time focusing of the radar data and it will send the results to the tow vehicle control computer. The positions will be shown on a moving map display, and the near real-time focusing results will be displayed for the calibration of the GPR operational parameters. This kind of design is more modular, and it makes the GPR/GPS/IMU system independent of any sensor trailer or tow vehicle configuration.

The modeling of the tropospheric delay for the ground stations is very accurate, on the order of 0.01m - 0.02m, which is adequate for the 0.05m positioning required for GPR phase measurements. The temperature, shock and vibration range of the IMU and GPS instruments is very wide, and therefore, it is not anticipated to have any problems, especially when shock and vibration mounting is used.

5.6.3 Conceptual Design of the Man-Portable Navigation System

The functionality of the man-portable GPS/IMU navigation system is very similar to the ground navigation system. The basic difference is that the man-portable system should be portable. Therefore, all of its components, ranging from the GPR antenna to the IMU system, should be portable components. As described below, the low weight requirement of the man-portable system will place a limit on the accuracy of the employed IMU system.

A block diagram of the man-portable system is shown in figure 25. This system consists of two units: the base unit and the rover unit. The base unit is the same as that employed for the airborne and ground systems. It consists of one computer, one dual-frequency GPS receiver, one radio receiver/transmitter, and a power amplifier — all of which are encased within a waterproof enclosure for continuous operation in outdoor, exposed environments. The power amplifier is used to operate the system over distances of 20 miles. Without an amplifier, the system can operate over distances of 5 to 10 miles, which will be sufficient for most of the UXO sites where a man-portable system is required. The rover unit consists of a portable computer, one hand held GPS receiver integrated with an IMU and a radio receiver.

The man-portable GPR unit should be built to operate in rough areas where the ground system is not able to operate. For this reason, the man-portable unit is housed inside a golf cart as shown in figure 25. The impulse generator (i.e., time-domain GPR) and the batteries are housed in the lower module of the golf cart. The GPS receiver, the computer with the display showing the moving-map, and the results of the near real-time GPR focusing are housed in the upper part of the golf cart. The transmit-receive antenna pair consists of orthogonal, resistively loaded dipoles. The IMU system is placed on the top of the GPR antenna, which is designed to slide on the ground (figure 25).

The LN-100 high-accuracy system, recommended for the ground platform, weighs 18.5 pounds, making it inappropriate for use in the man-portable platform. For this reason, the LN-200 IMU, which weighs only 1.54 pounds, is recommended for use. A full blown INS (LN-210) with an LN-200 IMU engine weighs 8.1 pounds. Therefore, it is recommended that for the man-portable system, the LN-200 IMU be tightly integrated with GPS, which will keep the weight of the GPS/IMU system much lower. The tight integration of the IMU with GPS will provide high accuracy navigation for longer periods of time with less than four satellites in view. The man-portable platform is very likely to track less than four satellites due to satellite signal obstructions caused by high trees with thick foliage. Furthermore, the IMU unit will provide the orientation parameters needed to transform the GPS phase center to the GPR phase center when the system is operating in rough terrain with high slope. The GPS antenna should be placed high enough so that the person operating the man-portable platform does not obstruct the GPS satellite signals.

It is evident from figure 9 that the LN-200 IMU unit can maintain an accuracy of 0.10m for about 1 minute. This period can be extended by several more minutes when less than 4 satellites are tracked and the GPS is tightly integrated with the IMU. However, if the positioning accuracy deteriorates to less than 0.15m, the man-portable platform should come to a complete stop and perform a ZUP. Employing an LN-100 IMU unit will provide longer periods between ZUPs, but it will make the system heavier and maybe non-portable. These factors should be taken into consideration when building a man-portable system.

As mentioned in the previous section, the required accuracy to focus the GPR measurements is 1/12 of the wavelength of the highest frequency, which is 0.05m, for a frequency of 500 MHz. If a man-portable platform moves with a speed of 1 mile/hour and the GPR measurements are recorded every 5 milliseconds (200Hz), then the distance between subsequent GPR measurements is 0.0022m. Since the required accuracy is 0.05m, it is recommended that the GPR measurements be averaged in time so that the time interval between subsequent GPR measurements corresponds to a displacement on the ground of 0.05m. This time interval for a platform moving with 1 mile/hour is 0.1125 seconds corresponding to 8.88(~9) Hz. Therefore, the highest GPR rate that can be used for a man-portable platform is 9 Hz.

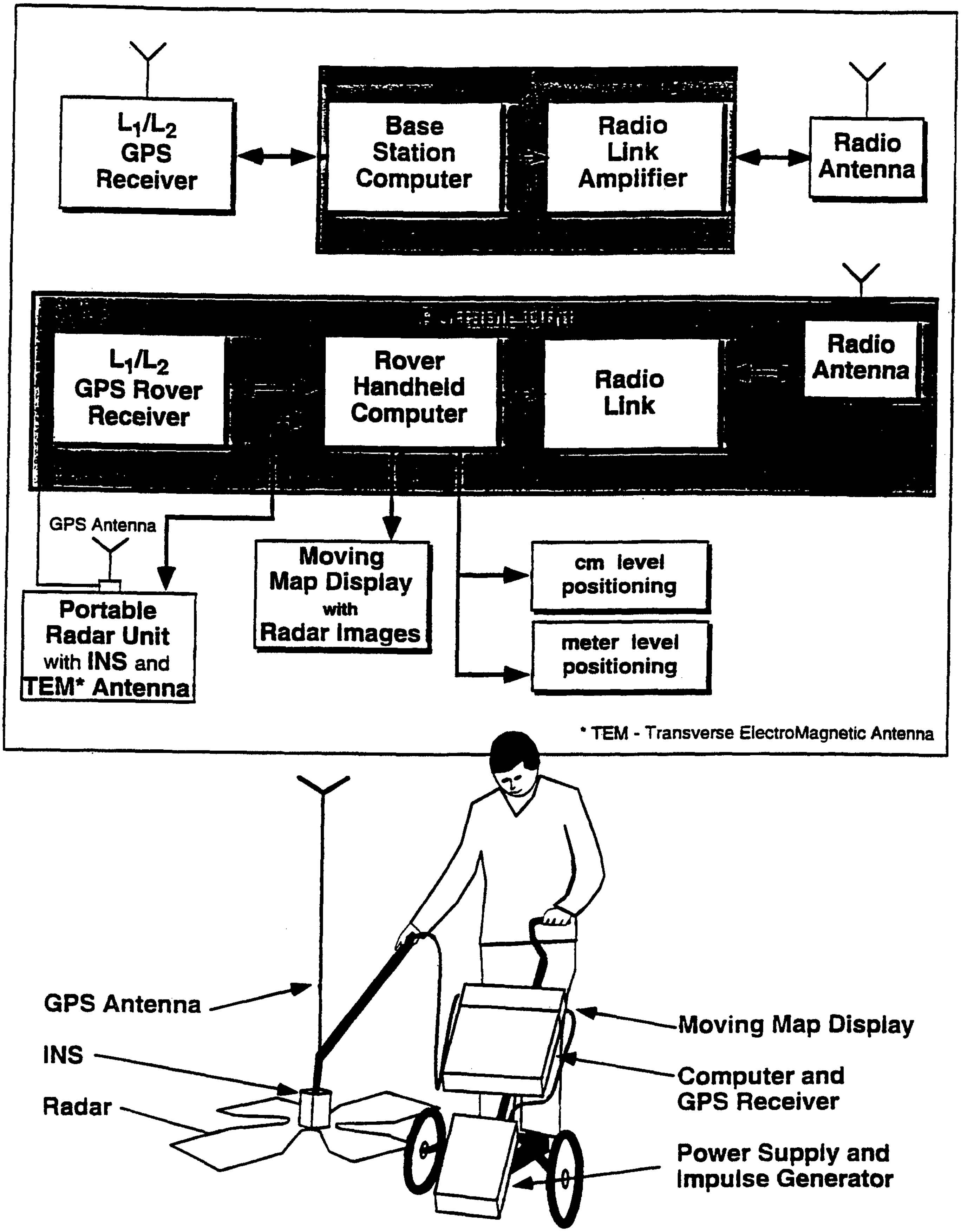

Figure 25 - Man-Portable Real-Time cm-level GPS Positioning System

Interference between GPS and GPR for the man-platform is possible, and can be detrimental to high accuracy navigation. The GPR system employed in the man-portable platform will be a time-domain GPR with an output power substantially lower than the output power of the frequency domain airborne system. Interference is possible and, therefore, it is recommended to conduct interference experiments between GPS and GPR using exactly the GPR system that will be employed in the man-portable platform.

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6.0 NAVIGATION DISPLAY

An integral part of each platform is a moving-map display showing in real-time the position of the moving platform overlaid on a moving map. This capability allows the operator of the multi-sensor platform to survey the areas of interest according to predetermined survey lines. The Center for Mapping has established the moving map display requirements, has performed an extensive search of all commercially available moving-map display modules, and has evaluated the advantages and disadvantages of these modules in meeting the system's requirements.

For the navigation of each platform it is important to follow predefined survey lines as closely as possible to ensure complete coverage of the surveyed area. The navigator must have access to accurate course information and corrections.

One role of the GPS is to provide course corrections: GPS gives the actual position, which is compared with the predefined desired course to determine the required course correction.

A moving map display will provide current course requirements and course correction in a usable form to the navigator. Moving map displays with GPS interfaces have been shown to be feasible and useful tools in current commercial products for aircraft navigation (e.g., LapMap) and ground based navigation (e.g., MapInfo).

6.1 Moving Map Display Requirements

The moving map software must be able to:

- Import maps (TBD format) at a variety of scales - if a map is not available, the software will show position relative to the user overlay.
- Display multiple maps (at least two) for coarse and fine detail.
- Provide online access to multiple maps, zoom and panning capability.
- Allow map manipulation, e.g., capability to alter map orientation, provide motion of position overlay rather than map.
- Import and display the predefined course as lines on the displayed map.
- Display additional data (overlaid text) to aid navigation. It is recommended that this data be updated when appropriate; e.g., with current position.
- Import GPS and INS position data via a database. GPS and INS data must be

accessible to other GPS software. If a direct link is used, the map software must not restrict accessibility.

- Interface with the selected GPS and INS.
- Provide coordinate transformations between map and GPS positions.
- Display current GPS position.
- Display actual course (from historical GPS/INS data).

Hardware and software interfaces to the moving map display include:

- Use of a portable or ruggedized system and use of special input devices.
- Implementation as a workstation vs PC-based system.
- Graphical User Interface (GUI) (XWindows vs MS Windows), software language interface (C vs proprietary interface such as a script language).

Other requirements that affect the moving map display include:

- Availability of maps of the surveyed area that would make the display more readable; putting the overlay in context with external features.
- The ability to navigate to the required accuracy and aspects of course correction will affect the usefulness of the system.
- The update rate of the map display must be sufficient for navigation at the expected vehicle speeds.

6.2 Approaches/Characteristics

The following is a survey of software products that appear to support the required capabilities. In particular, these products allow the user to import maps and overlay predefined survey lines.

Much of the commercial moving map display software has been developed for end-users in nautical and airborne navigation and is too specialized for these applications. The moving map display software products, which appear to support the required capabilities, have clearly been designed to support selected application markets with very different requirements than those of this project.

The following four software products have the capabilities to satisfy the requirements for the UXO, detection, identification, and remediation program:

- MapInfo
- XMap
- Geographic View/Tracker
- Field Notes

All of the above products allow the users to import maps in a variety of formats, to annotate, and associate points on the map with data from popular database products. All of these products provide zooming of the main map display and simultaneous display of text windows. The developer's software license may be required to overlay predefined course lines and to incorporate other requirements not available in the basic moving map display software products.

Direct GPS interfaces or serial port interfaces are optionally available for all of the above products. The direct GPS interfaces support many common GPS receivers, provide a summary of GPS information, and display the current GPS position on the moving map display.

Table 6 describes the basic capabilities and the pricing of the moving map software products mentioned above:

Table 6
Comparison of Moving Map Software Products

	Xmap - DeLorme Mapping	Map Info - Mapinfo Corp	Geographic View/Tracker - Blue Marble Geographics	FieldNotes - PenMetrics
Multiple Map Display	√	√	√	√
User overlay of predefined course lines	√	√	√	√
Platforms	UNIX, MS Windows	UNIX PC (DOS, MS Windows) Mac	UNIX PC (DOS, MS Windows) Mac	MS Windows
Direct GPS Interface	PC only	√	√	√

	Xmap - DeLorme Mapping	Map Info - Mapinfo Corp	Geographic View/Tracker - Blue Marble Geographics	FieldNotes - PenMetrics
Cost of Basic Products	$5,000 and up	≈ $1,500	≈ $1,000	≈ $1,000
Additional Costs	Developers software x $25,000 significant royalties on developed products	Developers software (script language) $800 and up	Developers software $5,000 and up	Developers software $2,000-$3,000

The least expensive (~$1,000 - $5,000) of the surveyed software products are designed primarily as end-user products for a variety of mass markets. Some products can be customized to a limited extent using simple proprietary script languages.

6.3 Recommendation

The moving map display product, required to support the UXO detection, identification, and remediation program, is not a typical application for the off-the-shelf commercial products. To minimize the risk and the customization costs, it is recommended to use an existing product that can be modified using the developer's software to meet the requirements of the UXO project.

With the above considerations in mind, the Center For Mapping has developed a relationship with Blue Marble GeoGraphics, a company with products with which CFM is already familiar. This will ensure the success of the moving map display product in support of the UXO detection, identification, and remediation technology.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Hardware/Software

Before proceeding with the Phase II development of the ground vehicular, man-portable and airborne platforms, several system integration issues should be addressed and a decision made on a common system by all parties involved in the development of the multisensor platforms. These issues include hardware platforms (e.g., PCS, workstations), software development language(s) (e.g., FORTRAN, ANSI C, C++), software communication (e.g., multiple CPUs, single CPU with multitasking and Interprocess Communication (IPC) capabilities), data interfaces to external hardware (e.g., ISA, EISA, VME bus), and GUI platforms (e.g., MS Windows, Win32, Xwindows). Appendix C presents a list of recommended hardware and software for use in UXO remediation efforts.

7.2 Electromagnetic Interference

Interference between GPS and GPR occurs when the GPR is transmitting in the neighborhood (±10MHz) of its third harmonics corresponding to the L1 and L2 GPS frequencies. This interference results in losses of lock to the L2 signal for the majority of the satellites. Missing the L2 data for most of the satellites will be detrimental to high accuracy positioning both in real-time and in post-processing. To solve this interference problem, it is recommended that the GPR be equipped with filters that will eliminate completely the transmission of the interfering frequencies.

7.3 GPS Configuration

For the GPS, it is recommended that either Trimble or Turbo-Rogue receivers, equipped with geodetic GPS antennas be used for the base stations. For the airborne platform, an airplane antenna should be employed.

7.4 Integrated GPS/INS

A combination of GPS with an INS or IMU will provide positioning information that covers the requirements of the GPR. For the ground-vehicle platform, a high accuracy IMU system is needed to maintain the required accuracies during the periods when the GPS satellite signals are not available due to obstructions. For the man-portable platform, a high accuracy IMU (LN100) would be preferable. However, the high accuracy IMU units tend to weigh more and, therefore, are not suitable for a man-portable system. For this reason, it is recommended that a low-cost low-weight IMU unit be used for the man-portable system. The lower accuracy IMU will require more frequent ZUPs when the GPS signals are not available. For an airborne system, the expected periods of GPS outages will be in the order of a few seconds. Therefore a low-cost, low-accuracy IMU (LN200) will provide the .07m accuracy requirements in both quasi real-time and in post-processing.

7.5 Map Display

The moving map display product, Geographic View/Tracker from Blue Marble GeoGraphics, is recommended to support the UXO detection, identification, and remediation program. It is an existing product, familiar to CFM, that can be modified using the developer's software to meet the requirements of the UXO project.

APPENDIX A

MATHEMATICAL MODEL FOR GPS ON-THE-FLY AMBIGUITY RESOLUTION

In the static environment, the changing satellite geometry allows the separation and estimation of the carrier phase integer ambiguities from the constant station geometry. In the dynamic environment, however, both station and satellite geometries are changing simultaneously. As a result, the separation of the integer ambiguities from the station-satellite geometry is more difficult, especially within short periods of time. In this case, code phase positioning in combination with OTF ambiguity resolution is used to estimate the carrier phase ambiguities.

Several OTF ambiguity resolution techniques have been proposed in the past ranging from ambiguity function techniques to ambiguity reparametrization (Counselman and Gourevitch, 1981; Hatch, 1990; Mader, 1992; Lachapelle et. al., 1993; Landau, 1993; Remondi, 1993; Abidin, 1993; Dedes and Goad, 1994; and Teunissen, 1994).

For short baseline lengths, the effect of the ionosphere is very small and therefore it can be neglected. In this case, the three measurement model takes the form (Dedes and Goad 1994):

$$DD(R_1) = DD(\rho) + DD(\varepsilon_{R1}) \qquad (1)$$
$$\lambda_1 \times DD(\phi_1) = DD(\rho) + \lambda_1 \times DD(N1) + DD(\varepsilon\phi_1) \qquad (2)$$
$$\lambda_2 \times DD(\phi_2) = DD(\rho) + \lambda_2 \times DD(N2) + DD(\varepsilon\phi_2) \qquad (3)$$

where DD is the double difference operator (difference of GPS measurements from two stations and two satellites at the same observation time) and R_1, ϕ_1, and ϕ_2 are the pseudorange, carrier phase L1, and carrier phase L2 measurements; ρ is the pseudorange affected only by tropospheric effects; N1 and N2 are L1 and L2 carrier phase ambiguities (the number of complete wavelengths by which the receiver phase measurements are in error when satellite tracking starts); ε_{R1}, $\varepsilon\phi_1$, and $\varepsilon\phi_2$ represent the noise affecting the pseudorange and the L1, L2 carrier phase measurements. Filtering the data using equations (1) through (3) yields the widelane ambiguities:

$$wd = DD(N1) - DD(N2) \qquad (4)$$

which together with the geometry-free L1/L2 carrier phase combination:

$$DD(\phi_1) - (77/60) \times DD(\phi_2) = DD(N1) - (77/60) \times DD(N2) + DD(\varepsilon\phi_1) - DD(\varepsilon\phi_2) \qquad (5)$$

form the basis for the ambiguity resolution. Proper filtering of the left side of equation (5) will reduce the effects of noise and multipath, but it will still be affected by unmodeled systematic affects of residual ionosphere, troposphere and multipath. For short filtering times and in the presence of systematic errors, the equations are not really equations but inequalities of the form:

$$-dw_1 \leq wd - (DD(N1) - DD(N2)) \leq dw_1 \quad (6)$$

$$-d\phi_1 \leq DD(\phi_1) - (77/60) \times DD(\phi_2) - (DD(N1) - (77/60) \times DD(N2)) \leq d\phi_1 \quad (7)$$

The value of dw_1 depends on the accuracy of the pseudoranges, and the value of $d\phi_1$ depends on accuracy of the carrier phases. Consequently, the value of dw_1 is usually much larger than the value of $d\phi_1$.

The solution to the ambiguity problem is to find the set of all possible *DD(N1)* and *DD(N2)* pairs for all satellites satisfying inequalities (6) and (7) with the constraint that all these pairs correspond to the same position in space. To solve this problem, the values for dw_1 and $d\phi_1$ should be estimated, and a searching range for *DD(N1)* and *DD(N2)* needs to be established. The values dw_1 and $d\phi_1$ of depend on the elevation angle of the corresponding satellite, and they can be established from their accuracy estimates.

The searching range of *DD(N1)* and *DD(N2)* is established by solving equations (4) and (5) and using the fact that a 0.1 cycle error in the geometry-free carrier phase ambiguities introduces an error of .353 cycles in the estimation of *DD(N1)* or *DD(N2)*.

For long baseline ambiguity resolution, the three measurement filter should be replaced with the four measurement filter, the geometry-free L1/L2 carrier phase should be replaced with the iono-free L1/L2 combination, and the *DD(N1)* and *DD(N2)* searching range should be established from the values and the accuracy of the *DD(N1)* and *DD(N2)* filter estimates.

APPENDIX B

MATHEMATICAL MODEL FOR INERTIAL NAVIGATION

The equation of motion of a body in a non-rotating, freely falling coordinate frame, called the **i-frame**, is given by

$$\ddot{r}^i = a^i + g^i \qquad (1)$$

where a^i is the specific force (accelerometer output), g^i is the total gravitational acceleration, and $\ddot{r}^i$ is the total acceleration (second derivative of the position vector). The i-frame is an inertial frame whose origin coincides with the center of mass of the Earth. The desired coordinates are usually given in a local, north-east-down (NED) frame, or **n-frame.**

Let ω^n_{in} be the rotation vector of the n-frame with respect to the i-frame expressed in the coordinate system of the n-frame, and let C^i_n be the transformation matrix from the n-frame to the i- frame. Then, differentiating $r^i = C^i_n r^n$ twice with respect to time and substituting into (1) yields:

$$\ddot{r}^n = -2\,\omega^n_{in} \times \dot{r}^n - \omega^n_{in} \times \omega^n_{in} \times r^n - \dot{\omega}^n_{in} \times r^n + a^n + g^n \qquad (2)$$

where $a^n = C^n_i a^i$; $g^n = C^n_i g^i$; and $(C^n_i)^{-1} = (C^n_i)^T = C^i_n$;

and where $\dot{C}^i_n = C^i_n [\omega^n_{in} \times]$ (3)

defines the dynamics of the orientation of the n-frame with respect to the i-frame, with $[\omega^n_{in} \times]$ denoting the skew-symmetric matrix of rotation rates, having the same effect as the vector product. The differential equations (2) and (3) above together define the dynamics of the body motion. The linear perturbation of these equations provides the relationship among the errors in position, velocity, and orientation of the system and the errors of the sensors. The complete derivations can be found in Britting (1971).

Introducing the velocity in addition to position, the second order differential equation (2) and (3) can be converted to a set of first-order differential equations describing the dynamics of the system with the following form:

$$\delta \dot{x} = F\delta x + Gw$$

where δx is the state vector consisting of orientation, position, velocity errors, gyro bias errors, accelerometer bias errors and scale errors. The vector w represents the white noise affecting the gyro and accelerometer measurements. The matrices F and G represent the dynamics and noise coefficient matrices respectively.

It is assumed that the position of the platform is observed directly with the GPS. The observation model which consists of only the observed GPS positions has the following form:

$$\delta y = H\delta x + v$$

where y are the observed GPS positions, x is the state vector and v is white noise affecting the GPS observations. The design matrix H has all of its elements zero except that three of its columns corresponding to the position, form together an identity matrix.

APPENDIX C

SUMMARY OF RECOMMENDED HARDWARE AND SOFTWARE

	Airborne	Ground	Man-portable
GPS (1), (2)	2 dual-frequency	2 dual-frequency	1 dual-frequency 1 hand-held
GPS antenna (1), (2)	1 ground plane or choke ring 1 airplane	2 ground plane or choke ring	1 ground plane or choke ring (2nd antenna on hand-held receiver)
Radio Modem (3)	1 RDDR-96 (UMF, 450-470 MHz)	1 RDDR-96 (UMF, 450-470 MHz)	1 RDDR-96 (UMF, 450-470 MHz)
INS (4)	LN-210 (including LN-200)	LN-100	LN-200
Moving Map Display (5)	Geographic View/Tracker	Geographic View/Tracker	Geographic View/Tracker

Manufacturers:

(1) Allen Osborne & Associates (805) 495-8420

(2) Trimble Navigation (800) TRI-MBLE

(3) Pacific Crest Instruments (800) 795-1001

(4) Litton Guidance and Control Systems (818) 715-2161

(5) Blue Marble Geographics (207) 582-6747

APPENDIX D

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DOCUMENT 4

Experimental Evaluation of the Apparent Temperature Contrast Created by Buried Mines as seen by an IR Imager

ADA 289856

By
J.R. Simard
November 1994

Defence Research Establishment Suffield
Ralston, Alberta (Canada)

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EXPERIMENTAL EVALUATION OF THE APPARENT TEMPERATURE CONTRAST CREATED BY BURIED MINES AS SEEN BY AN IR IMAGER (U)

BY

J.R. SIMARD

NOVEMBER 1994

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EXPERIMENTAL EVALUATION OF THE APPARENT TEMPERATURE CONTRAST CREATED BY BURIED MINES AS SEEN BY AN IR IMAGER

by

Jean-R. Simard

May, 1994

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ABSTRACT

The detection of buried mines is a problem of prime interest internationally. One potential method to succeed in this task is to use passive IR imaging to form thermal images of the soil surface. Even though this technique has been intensively investigated for the last 15 years, only few publicly reported studies show quantitative measures of the apparent temperature contrast at the soil surface above buried mines. This document aims to improve this situation. Apparent temperature contrasts are measured for different mine-soil combinations over 24 hours periods with a camera sensitive to long wave infrared (8-12 μm). The effect of the variation in burial depth is investigated and special attention is taken to differentiate the thermal effects associated with the soil disturbance from the mine itself. A maximum average of 2 degrees C in apparent thermal contrast is reported and this apparent thermal contrast disappears when the burial depth exceeds 8 cm for the case where the thermal disturbance is related to the buried mine only. A 50% increase ($\sim$ 3 degrees C) is observed when the thermal effect of the soil disturbance is present. Furthermore, this last apparent thermal contrast shows little dependency with the burial depth. These results are promising for the detection of mines buried in compacted soil. However, serious reservations about an acceptable false alarm rate and the duration of the thermal effect created by the soil disturbance are expressed.

SOMMAIRE

La détection de mines sous la surface du sol est un problème mondial. Une méthode pouvant avoir un potentiel de succès implique l'analyse thermique de la surface du sol à l'aide d'une caméra infrarouge. Même si cette technique a été intensément étudiée durant les 15 dernières années, très peu de mesures quantitatives du contraste de la température apparente à la surface du sol créé par des mines ensevelies ont été rapportées. Ce document vise à améliorer cette situation. Une série de mesures de ce contraste apparent a été réalisée pour différentes combinaisons de mines et de types de sol durant des périodes de 24 heures à l'aide d'une caméra sensible aux longues longueurs d'ondes infrarouge (8-12 μm). L'effet associé à la profondeur à laquelle la mine est enterrée a été analysé et une attention spéciale a été prise afin de différencier les effets thermiques reliés à la perturbation du sol de ceux reliés à la mine seulement. Un contraste maximum de la température apparente moyenne évalué à 2 degrés et disparaissant lorsque la mine est enterrée à une profondeur de 8 cm ou plus est rapporté lorsque l'effet thermique est associé à la mine seulement. Une augmentation de 50% ($\sim$ 3 degrés C) est observée lorsque l'effet thermique est associé à une perturbation du sol. De plus, ce contraste de la température apparente dépend très peu de la profondeur à laquelle la mine est enterrée dans ce dernier cas. Ces résultats sont prometteurs pour la détection de mines enterrées dans des sols compactés. Toutefois, de sérieuses réserves à propos d'un taux de fausses alarmes acceptable et de la durée de l'effet thermique créé par la perturbation du sol sont mentionnées.

ACKNOWLEDGEMENT

I would like to express my gratitude to Mr.Wayne Sirovyak who prepared the experimental set-up and wrote the data acquisition software. I would also like to thank him for kindly agreeing to spend nights on the tower to ensure that the experiment was carried out without interruption.

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1. Introduction

The detection of minefields has been a subject of strong interest for the last 40 years. This interest was primarily dictated by tactical considerations under a war scenario. But in the last 15 years, with the increase of peacekeeping activities in countries decimated by civil wars and other social disorders, the interest for mine detection (and clearance) has taken on even more importance. Many methods to perform this task have been proposed (imaging, magnetic, nuclear, vapor trace detection,...). However, one of the methods which has been researched actively since the early 70's is IR imaging. Recently, a few research groups from the United States (RECON/OPTICAL Inc. [2, 3], Wackenhut Advanced Technology corp. [4], WES [5], ERIM [6]) have reported attractive capabilities in the detection of buried minefields with passive IR imaging systems. Furthermore, other NATO countries (UK, France) have also unofficially reported similar capabilities. Notwithstanding that such detection capabilities have been reported, little measurements have been performed (and published [7, 8, 9]) to evaluate quantitatively the apparent contrast in temperature that can be expected from buried mines when observed with an IR imager. The work done by Del Grande [7, 8] shows impressive results about the temperature contrasts of buried objects, filled holes and grass-covered sites with a dual-band IR imaging system. The work presented in this report aims to complete this research by evaluating the apparent temperature contrasts of buried mines over a 24-hour interval for different burial depths and types of soil. In addition, the thermal effect of disturbed soil is also investigated.

The structure of this report is as follows. In the first chapter, a simple theoretical basis to interpret qualitatively the thermal mechanisms involved in the behaviour of buried mines is shown. The second chapter presents the experimental results. These results describe the apparent temperature contrast at the soil surface where mines are buried. The measuring instrument is an IR camera (8-12 μm) and acquisitions are made over 24-hour periods. Furthermore, these acquisition periods are achieved for 3 types of anti-tank mine and 3 types of soil: top soil, clay, and masonry sand. Special attention is taken to differentiate between the case of a mine buried in undisturbed soil [1] and the case of a mine buried in disturbed soil. This last case refers to the situation where all the surrounding soil to the burial site is homogenized to eliminate the thermal effects associated with soil disturbance. Chapter 3 discusses the results of the experimental section. The thermal contrasts observed between different trials, the thermal mechanisms involved, and the false alarm rate problem are approached. Finally, Chapter 4 summarizes the principal observations reported in this document.

[1] Relates to the situation where a hole is dug to bury the mine.

2. Theory

The heat transfer mechanisms dictating the thermal behavior of the soil surface during a 24-hour period are well known. In most cases, this thermal behavior is analyzed by defining the soil layer as a one-dimensional problem. This approach is acceptable for the case of buried mines [1] where the model is defined as two layers (see figure 2.1). In this model, the first layer represents the soil above the mine and the second represents the mine itself. With this structural model, differential equation(s) and boundary conditions originating from thermodynamic theory can be applied and solved for the particular problem of buried mines.

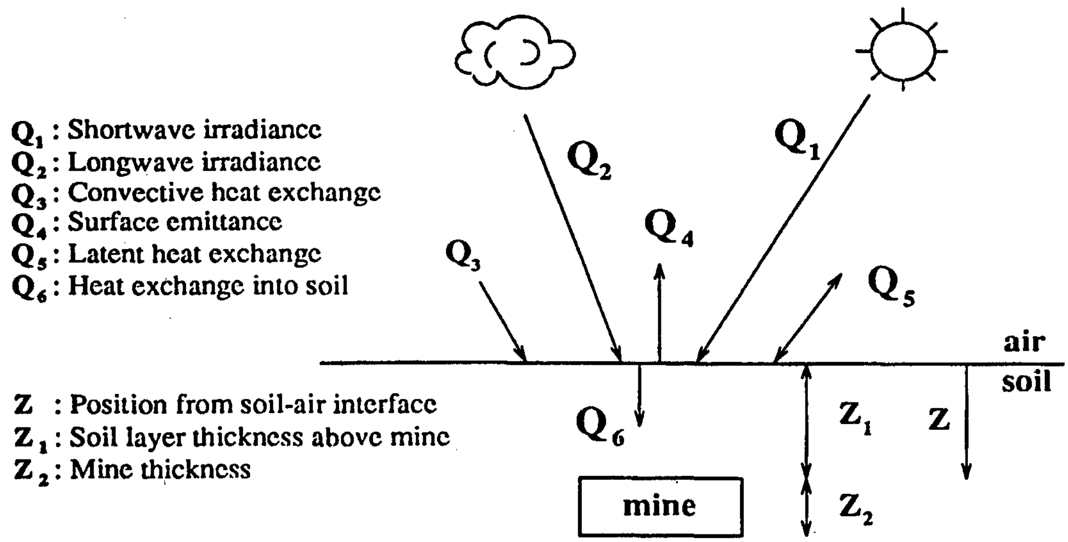

Figure 2.1: Schematic representation describing the thermodynamic model of a buried mine and its thermal interaction with the atmosphere. In this scheme, Q_6 represents the heat exchange with the soil underlayers and is modelled by the right side of equation 2.1.

The first differential equation historically [10] used to solve this kind of problem was the simple heat transport equation:

[1] This is not completely true for the situation where the burial depth has a dimension comparable to the lateral size of the area of interest above the mine. However, for the type of information that can be gathered realistically with this modeling technique, this one-dimensional approach is satisfactory.

$$\frac{\partial T(z,t)}{\partial t} = \kappa \frac{\partial^2 T(z,t)}{\partial z^2} + Q(z,t) \qquad (0 \leq z \leq z_1 + z_2).$$

In this equation, T is the temperature, z is the vertical position, t is the time, κ is the thermal diffusivity (defined as the ratio between the thermal conductivity and the product specific heat $\times$ specific mass) and $Q(z,t)$ is the total heat source present at the position z and time t. It is with this type of differential equation that results were first obtained: Carslaw [11] presented an analytical solution of this classical heat conduction equation for a semi-infinite solid conductor with a sinusoidal temperature variation at its surface. His results predict that the amplitude of the "thermal wave" inside the solid follows an exponential decay with a penetration depth z_e equals to $(P\kappa/\pi)^2$ where P is the period of the sinusoidal temperature variation. With this model and for most natural materials found in soils, this penetration depth is of the order of 10 cm for a 24-hour temperature variation period [9]. This result gives a first useful tool to figure out roughly the distance from the soil surface where atmospheric heat exchange changes have some thermal effects.

However, to obtain a more accurate insight in the thermal behavior of the soil surface, it is necessary to take into account that the soil is not an ideal solid but a porous material. This implies that the heat flow can be carried by moisture transfer (latent heat transfer) in addition to the classical conduction effect. To include this effect in the differential equation model describing the physics of heat transfer in soils, two combined differential equations, one for the heat flow conduction and the other for the moisture flow, have to be solved [12]. In one dimension, these equations are derived as [12, 13]

$$\left.\begin{array}{rcl} \frac{\partial \Theta}{\partial t} & = & \frac{\partial}{\partial z}\left\{D_T \frac{\partial T}{\partial z} + D_\Theta \frac{\partial \Theta}{\partial z} + k_h\right\} \\ C_v \frac{\partial T}{\partial t} & = & \frac{\partial}{\partial z}\left\{K_T \frac{\partial T}{\partial z} + K_\Theta \frac{\partial \Theta}{\partial z} + k_h \rho_m h_m\right\} \end{array}\right\} \qquad 0 \leq z \leq z_1 + z_2$$

with the following definitions:

Θ :	Moisture content,
ρ_m :	Density of water,
h_m :	Specific enthalpy of water,
k_h :	Hydraulic conductivity,
C_v :	Volume averaged heat capacity,
$D_{T,\Theta}, K_{T,\Theta}$:	Nonlinear transport coefficients.

The first difficulty in the solution of this set of differential equations is embedded in the presence of non-linear and time dependent coefficients which are dictated by the soil properties, moisture content and temperature. General representations of the coefficients and other parameters of these equations can be found in the literature [14]. With this information, a numerical solution of these differential equations, even if complex, can be attempted. The second difficulty, which is associated with the boundary problem, is much more difficult to solve. According to the definition of the model (see figure 2.1), three boundary conditions have to be satisfied:

1. Boundary between the soil and the bottom surface of the mine [2] ($z = z_1 + z_2$)

$$Q(z_1 + z_2, t) = 0 \quad \text{and} \quad e(z_1 + z_2, t) = 0$$

2. Boundary between the top surface of the mine and the soil ($z = z_1$)

$$\begin{aligned}\lim_{\epsilon \to 0} Q(z_1 - \epsilon, t) &= \lim_{\epsilon \to 0} Q(z_1 + \epsilon, t) \\ \lim_{\epsilon \to 0} e(z_1 - \epsilon, t) &= \lim_{\epsilon \to 0} e(z_1 + \epsilon, t)\end{aligned}$$

3. Boundary between the soil surface and the atmosphere ($z = 0$)

$$Q(0,t) = K_{\mathrm{T}}\frac{\partial \mathrm{T}}{\partial z} + K_{\Theta}\frac{\partial \Theta}{\partial z} + k_h \rho_m h_m \tag{2.1}$$

$$e(0,t) = D_{\mathrm{T}}\frac{\partial \mathrm{T}}{\partial z} + D_{\Theta}\frac{\partial \Theta}{\partial z} + k_h \tag{2.2}$$

In addition to the spatial boundary conditions, initial conditions have also to be satisfied. In most situation, this condition can be assumed to be an initial homogeneous temperature and moisture content:

$$\left.\begin{aligned}\mathrm{T}(z,t) &= \mathrm{T}_0 \\ \Theta(z,t) &= \Theta_0\end{aligned}\right\} \qquad [0 \le z \le (z_1 + z_2)] \cap t \le t_0.$$

The major difficulty with these conditions is at the soil-atmosphere interface (3^{rd} boundary condition). A minimum series of five principal heat-exchange mechanisms included in $Q(0,t)$ are identified at this interface:

- **Absorbed shortwave irradiance** ($\lambda \le 3\ \mu m$). This is essentially the energy directly injected by the sun into the soil (diffuse or direct). Represented by Q_1 in figure 2.1.
- **Absorbed longwave irradiance** ($\lambda > 3\ \mu m$). Because the sun has little emission in this band, this source of irradiance originates mostly from the sky and the surrounding terrain and becomes important at night. Represented by Q_2 in figure 2.1.
- **Convective heat exchange.** This heat exchange is performed by the air movement above the soil surface and depends on the soil surface geometry, surrounding obstacles, and wind temperature and velocity. Represented by Q_3 in figure 2.1.

[2]For this condition, we usually assume that the mine is sufficiently deep that no heat or moisture flow ($e(t)$) is exchanged.

Very sensitive	Moderately sensitive	Very insensitive
Air temperature	Relative humidity	Air pressure
Solar irradiance	Target height	Cloud cover (high)
Solar absorption coefficient	Wind speed	Time step
Thermal emission coefficient	IR sky irradiance	Thermal diffusivity
Top layer heat conductivity	Thermal conductivity	Grid spacing
Cloud cover (middle level)	Bottom boundary flux	
Cloud type		24-hr repetitions
Initial conditions		

Table I: Relative sensitivity of the thermodynamic model to several parameters as analyzed by Jacobs [1].

- **Surface emittance.** This mechanism represents the radiative emission of the soil surface because of its temperature. It is the mechanism which allows the monitoring of the temperature variation at the surface with the IR imager. Represented by Q_4 in figure 2.1.

- **Latent heat exchange by condensation/evaporation.** This process includes principally the water condensation and evaporation created by dew and to a certain extent, the evaporation of rainfall. Represented by Q_5 in figure 2.1.

This series of heat-exchange mechanisms, which is far from complete, introduces a large number of parameters (amount of high and low clouds, incident angle of sun rays, surrounding ground morphology, soil reflectivity,...). To make a direct and absolute model of the heat and mass transfer process, these parameters have to be evaluated empirically with sufficient precision. Usually, this task is almost impossible to perform without direct monitoring of the surface of interest. This limitation makes this model of little utility in precise thermal prediction of remote soils. However, this model introduces useful clues in the characterization of the relative importance of each of these parameters. This information could lead to a better understanding of the thermal variations observed in buried mines. Jacobs [1] studied the case of a concrete slab laying on the soil under clear and overcast conditions and after he carefully evaluated each parameter, he published the relative sensitivity of the model to several of them. These results are reproduced in Table I. Even if these results are associated with a concrete slab, it is believed that many results of this study are applicable to the case of buried mines.

To translate the results of Table I to the case of buried mines, it is important to realize that the detection of these buried mines with an IR imaging system is done by characterizing the local temperature contrast of the soil surface just above the buried mine compared to the immediate surrounding soil surface. This implies that many of the parameters listed in Table I (air temperature, solar irradiance...) which applied to large soil surface will have little effect in the local temperature contrast created by the buried mine in comparison to parameters which have a local impact (top layer heat conductivity, bottom boundary flux...). This concept should be kept in mind when conclusions presented in Table I are used to interpret general thermal mechanisms involved in the buried mines scenario.

3. Experimental Results

The previous chapter showed a theoretical model describing how buried mines can disturb the temperature uniformity of the soil surface. In this model, it was reported that a large number of empirical factors needs to be known with precision to reproduce the thermal variation of this soil surface with sufficient accuracy. Consequently, it has been decided to reproduce experimentally the situation where a soil layer covers mines and to monitor the thermal variations of the interface atmosphere-soil. This experimental verification will not specify precisely the thermal variations expected in all situations but what thermal variations can be observed. These observed experimental thermal variations will be presented in this chapter after the description of the experimental set-up used.

The simulation of the mine-soil compounds was performed with three types of anti-tank replica mines: the PM-60, the TMB-D, and the TMN-46 [1]. Each of these replica mines has been filled with Uniroyal Adiprene, a plastic. This material has the particularity to closely simulate the thermal properties of the TNT without involving any explosive product. Each of these three types of mine was buried in three different types of soil: masonry sand, clay, and prairie top soil. For each mine-soil combination, four (three for the TMB-D) identical mines were buried at four different depths. These depths varied from 1 cm to 8 cm. The arrangement of the soil and the mines was done in a wood box with the following dimensions: $8' \times 4' \times 1.5'$ ($\sim$2.5m x 1.25m x 0.5m). These dimensions are sufficient to keep the distance between each mine and between the mines and the walls of the box to a value greater than the IR thermal diffusion length. Finally, it should be mentioned that each time the buried mines were interchanged from one type to one of the two others, the soil was mixed to minimize any inhomogeneity in density.

The wood box containing the buried mines was observed from a tower with an angle of view having a 25 degrees incline with the vertical. For each mine-soil combination, a 24-hour trial was carried out where IR images of the soil surface covering the buried mines were taken each 1/2 hour. The type of camera used was the Agema model AGA 782 with the following characteristics: long wavelength IR sensitivity (8-12 μm), thermal sensitivity, as claimed by the manufacturer, of 0.1 °C, display resolution of 100 elements/line with 280 lines/frames (interlaced with 4:1 ratio), and a Field of View (FOV) of 3.5°x3.5°. With the distance camera-object plane at 15 meters, this FOV allowed the observation of the

[1] Refer to Appendix A for a photograph of each of these mines.

soil surface without including the wooden border of the box. This configuration has the advantage of eliminating potential thermal inhomogeneities in the image and of reducing possible wrong thermal level settings associated with the auto-gain function of the camera. The calibration of the IR camera was done in laboratory with a thermally calibrated source.

The following figures show the apparent temperature contrast found for each trial. These apparent temperature contrasts were obtained by subtracting the average pixel reading of the image of the soil surface above the buried mines from the surrounding soil surface [2]. In addition, the air temperature [3] was sampled and the cloud cover conditions [4] were evaluated at regular intervals during the trial. This information is shown on a second graph for each trial. Unfortunately, the fixed orientation of the tower imaging facilities created a period during the 24-hour of acquisition cycle where the shadow of the tower passed over the wood box. The time of passage of the tower's shadow is about 1/2 hour and will be identified for each trial where sunlight is not negligible. Finally, two trials were specifically performed to verify the thermal behaviour of mines buried in real soil. These trials are named 'mines buried in undisturbed soil' to emphasize the fact that inhomogeneities in the soil are created when a hole is dug. To isolate this hole digging effect, one of the trial was done with mines buried in holes and the second trial was done with the same holes but without the mines. The analysis of these results are presented in the next chapter.

[2] An image giving the precise position of each buried mine for each particular trial was taken. These pictures allowed the identification of the imaging pixels of the soil above the buried mines and these surrounding these areas.

[3] Temperature readings were done from a shadow corner shielded from the wind outside the shelter.

[4] These cloud cover conditions represent only a rough evaluation of the solar, cloud, and sky irradiation during the trial.

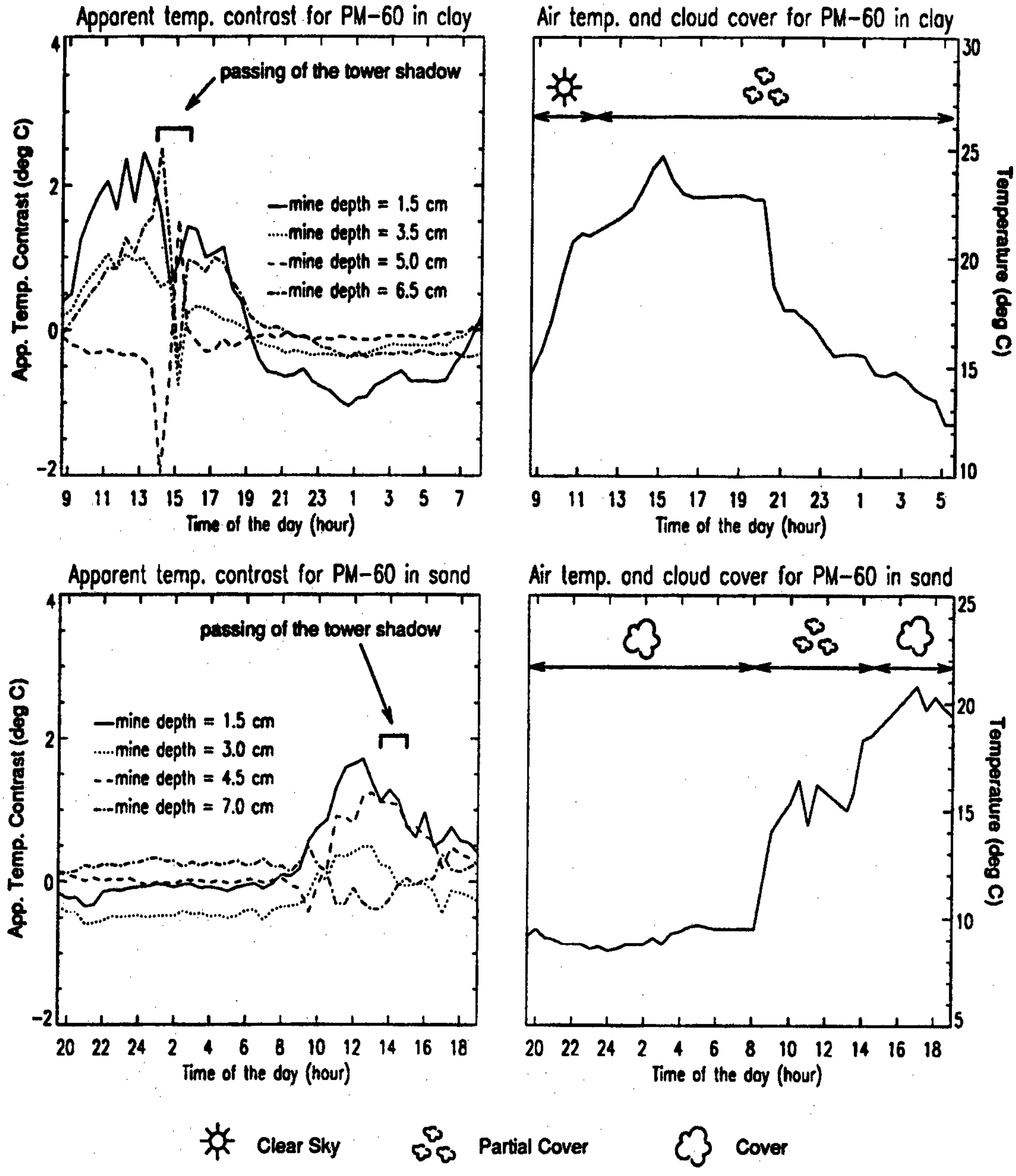

Figure 3.1: Apparent temperature contrast variation for the PM-60 replica anti-tank mine buried in clay and sand. The PM-60 and clay trial was performed August 18-19, 1993 and the mines were laid August 10, 1993. The PM-60 and sand trial was performed August 25-26, 1993 and the mines were laid August 25, 1993.

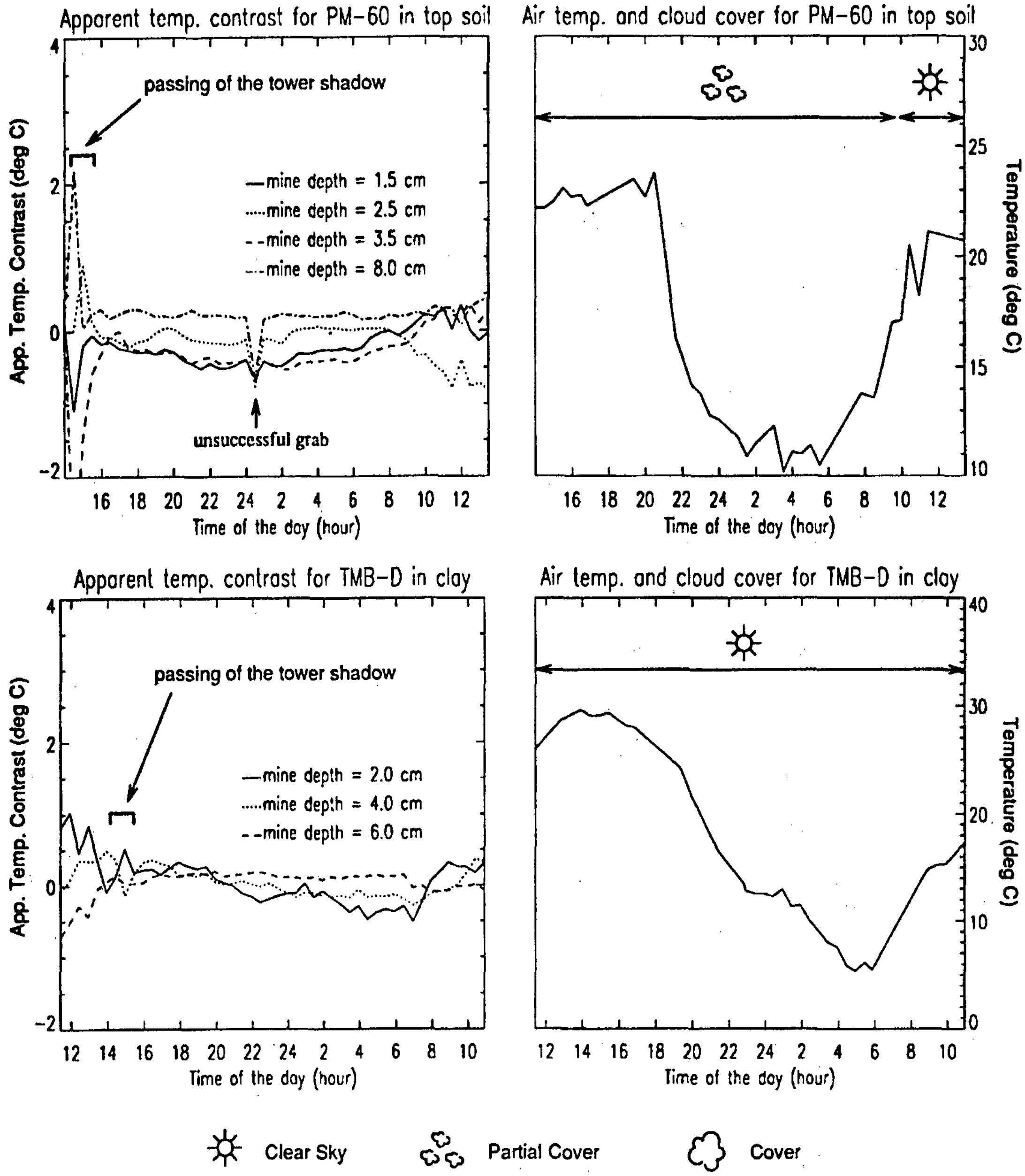

Figure 3.2: Apparent temperature contrast variation for the PM-60 replica anti-tank mine buried in prairie top soil and the TMB-D replica anti-tank mine buried in clay. The PM-60 and prairie top soil trial was performed July 21-22, 1993 and the mines were laid July 20, 1993. The TMB-D and clay trial was performed August 23-24, 1993 and the mines were laid August 23, 1993 at 09:00.

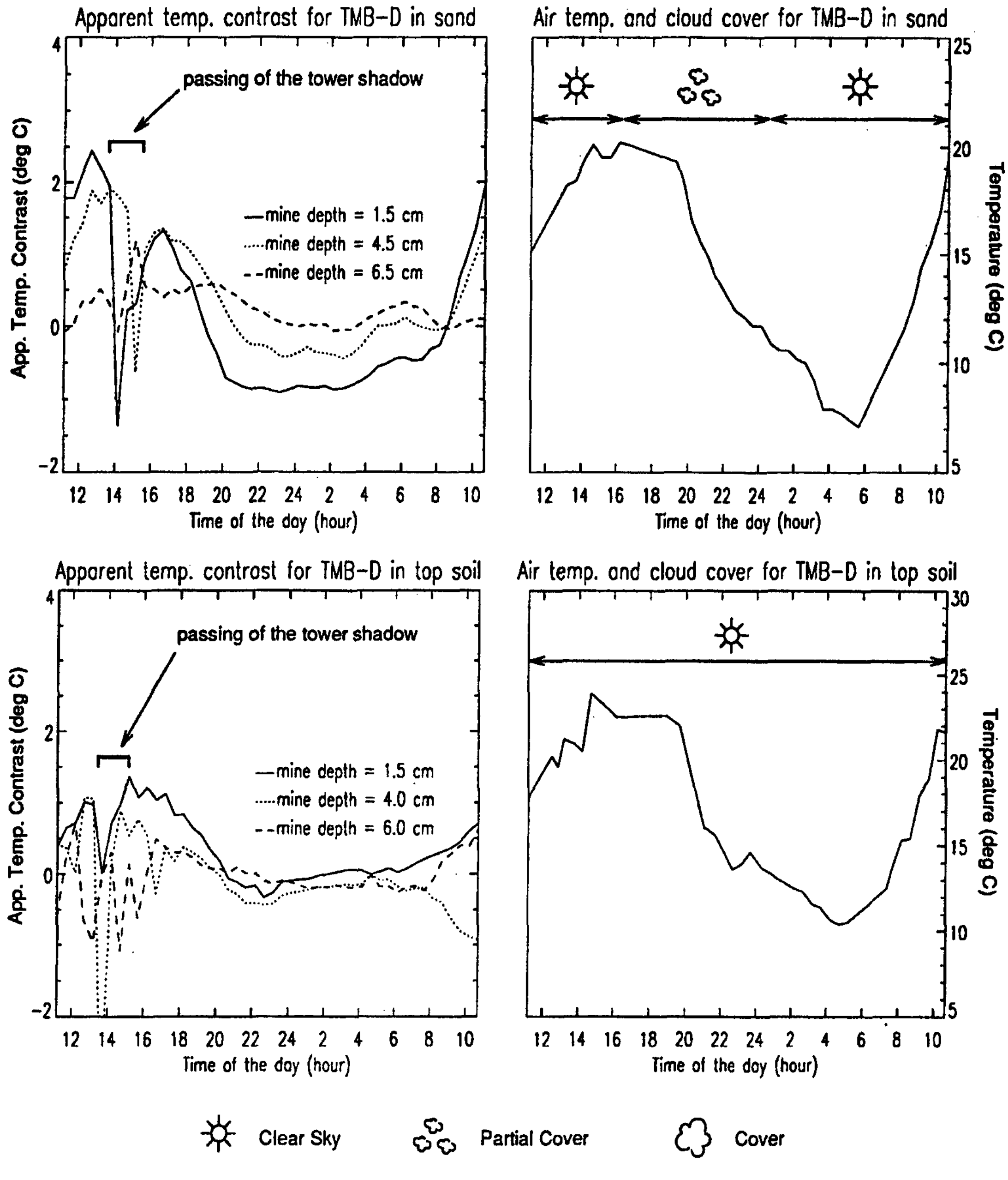

Figure 3.3: Apparent temperature contrast variation for the TMB-D replica anti-tank mine buried in sand and prairie top soil. The TMB-D and sand trial was performed August 30-31, 1993 and the mines were laid August 26, 1993. The TMB-D and prairie top soil trial was performed August 3-4, 1993 and the mines were laid August 2, 1993 at 16:30.

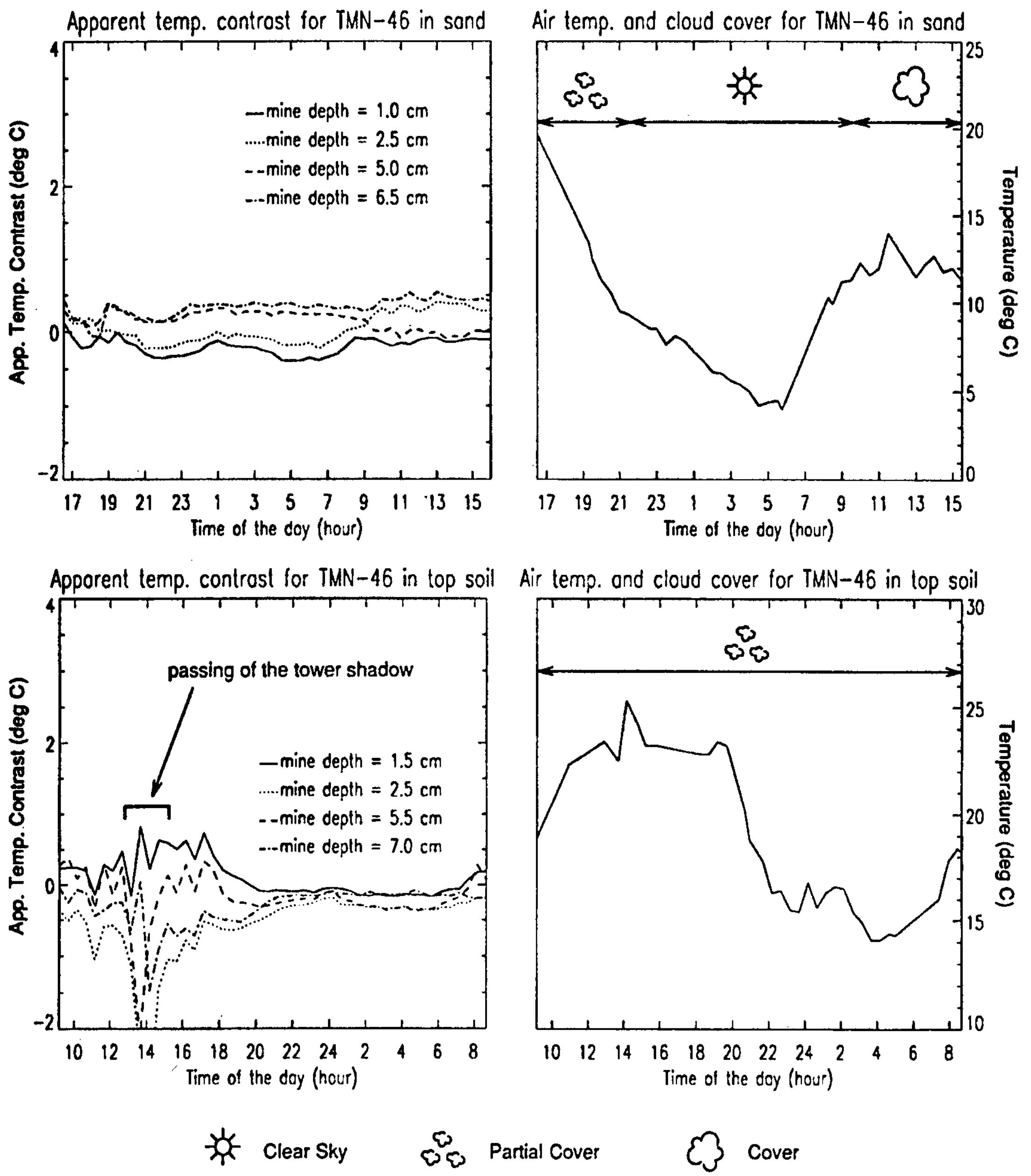

Figure 3.4: Apparent temperature contrast variation for the TMN-46 replica anti-tank mine buried in sand and prairie top soil. The TMN-46 and sand trial was performed August 24-25, 1993 and the mines were laid August 24, 1993 at 14:30. The TMN-46 and prairie top soil trial was performed July 19-20, 1993 and the mines were laid July 15, 1993.

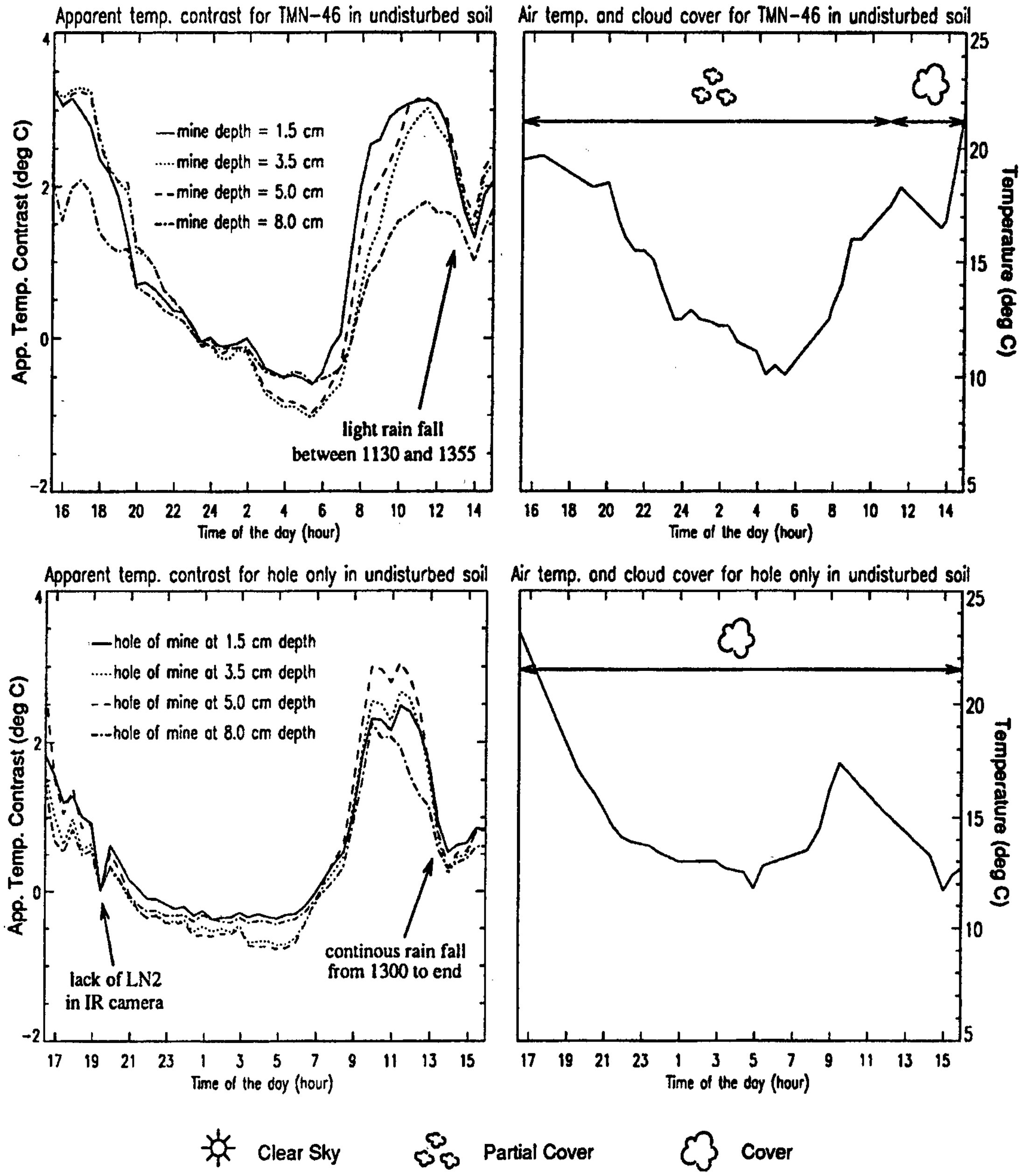

Figure 3.5: Apparent temperature contrast variation for the TMN-46 replica anti-tank mine buried in undisturbed soil and the apparent temperature contrast variation of the same holes but without the TMN-46 anti-tank mines. The buried site was grassless. The TMN-46 burial in undisturbed soil trial was performed July 5-6, 1993 and the mines were laid July 5, 1993 at 11:00. The hole only trial was performed July 6-7, 1993 and the arrangement of the soil was done July 6, 1993 at 16:00.

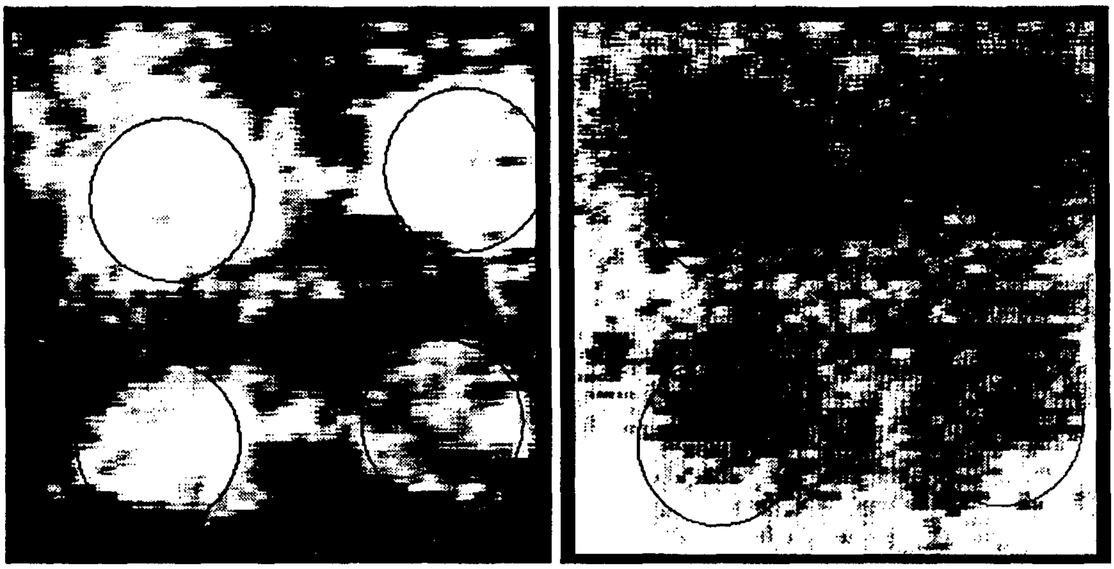

Figure 3.6: Apparent temperature contrast observed with the IR camera for the TMN–46 replica anti–tank mine buried in undistributed soil at the peak contrast during day and night time. The image showing the peak contrast during the day time (left image) was taken at 16:55 and the one showing peak contrast during the night time (right image) was grabbed at 05:25 during the trial of July 5–6, 1993. The trial corresponds to that presented in Figure 3.5. For the left image, the apparent temperature range between a black pixel and a white pixel corresponds to 3.5° C. For the right image, the apparent temperature difference between black and white pixels is 3°C. The circles show the position of the buried mines.

4. Discussion

As mentioned in the theoretical section, the thermal characteristization of buried mine-like objects is a delicate task. The numerous parameters (sunshine level, air temperature, humidity,...) involved in this thermal behaviour make comparison between distinct 24-hour trials very difficult to perform. Consequently, as a result of the experimental process chosen here (where each 24-hour trial was done with one type of mine and one type of soil), precise comparisons between results with different types of mine or soil are inapplicable. However, following the experimental results presented in this report, general observations for the different mine-soil combinations can be tentatively put forward [1] and temperature contrasts reported give a good estimate of what can be observed in similar situations.

Before presenting the general observations that can be mentioned with reasonable trust from the experimental results found in this report [2], it is important to differentiate the case of mines buried in undisturbed soil from that of mines buried in disturbed soil. Here we associate mines buried in undisturbed soil to the usual situation where a hole is dug to bury a mine without modifying the surrounding soil (case shown in figure 3.5). On the other hand, mines buried in disturbed soil refers to the case where the soil surrounding the buried mine has been mixed (homogenized) to eliminate the thermal effect created by the hole digging action itself (cases shown in figures 3.1, 3.2, 3.3, 3.4). With this difference stated, general observations about the thermal behaviour of buried mines can be postulated as follow.

1. **Mines buried in disturbed soil:**

    - An average maximum thermal contrast equivalent to 2 deg C can be observed.
    - No mine-soil combination studied in this report shows observable thermal contrast for a soil layer above the mine greater than 8 cm.
    - As expected, the thermal contrast decreases with the depth at which the mine is buried.

[1] More trials and data acquisitions should be accumulated to confirm statistically these preliminary observations.

[2] It should be mentioned that the observations enumerated here were not only based on the graphs shown in section 3 but also on the visual study of the 48 images taken during each 24-hour trial.

- For some of the 24-hour trials, the thermal contrasts created by the buried mines were observable during night time but not during day time.
- The PM-60 and TMB-D types of mine (see appendix A) seem to show greater thermal contrast than the TMN-46 for the three types of soil studied in this report (a possible explanation for this result is the greater thickness of the PM-60 and TMB-D compared to the TMN-46).
- The experimental measurements described in this report do not show clearly that one type of soil enhances the thermal contrast of buried mines more than any of the two others.

2. **Mines buried in undisturbed soil:**

- An average maximum thermal contrast equivalent to 3 deg C can be observed. This represents an increase of approximately 50% in thermal contrast compared with the results obtained with mines buried in disturbed soil.
- The observed thermal contrasts show little dependency with the depth at which the mine is buried.
- The thermal contrast associated with the holes dug and refilled with and without the mines is comparable.
- A rainfall will considerably reduce the temperature contrast. This can be explained by a temperature homogenization effect at the soil surface by the water. This effect should be the same for the case of mines buried in disturbed soil.

With these observations, an important conclusion to emphasize is that the local perturbations of the physical properties of the soil when a hole is dug and filled with or without a mine in undisturbed soil is largely responsible for the thermal contrast observed. This thermal behaviour of buried mines in undisturbed soil can be explained by considering the local change in density of the soil layer above the mine by the action of digging and refilling a hole [3]. In this situation, a reduction in soil density implies an increase in porosity. Following the theoretical analysis presented in chapter 2, it has been mentioned that the thermal model describing soils has to include the classical thermal conductivity through solid and the latent heat transport by moisture. Consequently, we can reasonably assume for the weather conditions and the prairie soil types used during this trial that the increase in porosity reduces more the thermal conductivity of the soil than it increases its latent heat transport efficiency. As a result, the overall heat drain through the soil is locally reduced which forces the other heat dissipation processes to increase. One of these dissipation processes is the radiative emission (surface emittance) and because the increase of this dissipation process implies a temperature rise, local temperature inhomogeneities will build

[3]The change in soil density resulting from this operation is well known in civil engineering.

up at the soil surface where holes were dug and filled. From the measurements obtained in this report, these local temperature inhomogeneities are large enough to be observed with commercial IR imagers.

However, an important question which has not been addressed in this report is the duration of these soil thermal inhomogeneities. From the time scale involved during the trial which has produced the experimental data, we can assume that the reported temperature contrasts are valid for at least a week. We can also assume that eventually, with the help of the weather and time, these soil inhomogeneities will disappear. At that moment, the mechanism responsible for the thermal contrast will be related only to the presence of the buried mines, which is equivalent to the cases of the mines buried in disturbed soils presented in this report.

From the preceding discussion, it appears that a passive IR imaging technique should have a reasonable success (close to 100%) for detecting buried mines (metallic or not) for scenarios where four conditions are present: the soil surface to inspect can be observed directly (no grass cover), the whole area of interest is submitted to similar irradiation (shadows from trees or little bumps can cause thermal inhomogeneities), the soil to inspect is naturally compacted [4], and the mine's burial is sufficiently recent. A potential scenario including these four conditions is the regular inspection of a dirt road for potential buried mine threats.

Finally, an analysis of the detection of buried mines using a thermal imager would not be complete if the problem of false alarm was not discussed. The potential sources of false alarms with this detection technique can be numerous. The apparent temperature recorded by an IR imager is not directly related to real temperature change in the scene observed. This results from the basic operating principle of the IR imager which is to perform a two-dimensional mapping of the amplitude of the incident IR radiation. For an imager based on longwave IR radiation (8-14 μm), the major portion of the incoming radiation originates directly from bodies at ambient temperature. However, a small change in emissivity (and reflectivity) in a spectrum interval where a non-negligible amount of sun incident radiation is present can significantly change the energy absorbed locally by the soil. This increase of absorbed energy modifies the local thermal equilibrium and contributes to a localized temperature increase. This implies that small local changes in emissivity at the soil surface could produce apparent temperature changes comparable to that created by a buried mine. This small local emissivity change can be created by a dry water hole which has accumulated a layer of small rocks with clay or other local changes in soil type at the surface (gravel patch, sand pit). In most cases, these differences in emissivity can be identified by visual inspection or this effect can be reduced by doing night inspection. Other potential sources of false alarms are when there is the presence of heterogeneous objects buried close to the surface or when a hole was dug and filled without a mine. In both cases, direct mechanical inspections have to be performed. It is certain that a non-negligible false alarm rate will be present in most scenarios. Martin Marietta reports a false alarm rate of less than one

[4]Sand on a beach is a good example of soil type which is not naturally compacted.

over 20 m^2 [15] (with 100% detection efficiency) with one IR band imager (8-12 μm) and neural network image analysis, This false alarm rate corresponds to one false alarm each 5 meters of travel on a 4 meter wide road. A level of false alarm of this magnitude makes this detection technique much less attractive. However, the addition of secondary information tools (metal detector, nuclear detection,...) to this technique should improve this false alarm rate.

5. Conclusion

The detection of buried mines is a problem of prime interest internationally. One potential method to succeed in this task is to use passive IR imaging to form thermal images of the soil surface. Even if this technique has been intensively investigated for the last 15 years, few quantitative measurements of the apparent temperature contrast at the soil surface above buried mines have been publicly reported [7, 9]. This document aimed to improve this situation. To help in the interpretation of the results presented, a simple introduction to the thermal mechanisms associated with buried objects has been given. The apparent temperature contrast was measured for different mine-soil combinations over 24-hour periods with a camera sensitive to long wave infrared (8-12 μm). The effect of the variation in burial depth was investigated and special attention was taken to differentiate the thermal effects associated with the soil disturbance from the mine itself. A maximum average of 2 degrees C in apparent thermal contrast is reported and this apparent thermal contrast disappears when the burial depth exceeds 8 cm for the case where the thermal disturbance is related to the buried mine only. A 50% increase ($\sim$ 3 degrees C) is observed when the thermal effect of the soil disturbance is present. Furthermore, this last apparent thermal contrast shows little dependency with the burial depth. These results are promising for the detection of mines buried in compact soil where the thermal effects of the soil perturbation are not negligible. However, serious reservations should be kept in mind about the false alarm rate which can considerably reduce the effectiveness of this method and the duration of the thermal effects created by the soil disturbance. Further trials should be designed and performed to evaluate this false alarm rate for different scenarios and to evaluate the time dependency of this soil thermal perturbation effect.

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Appendix A

Photographs of the Mines Used in this Study

In this appendix, photographs of the three different anti–tank mines used in this study are shown. Their names and the construction materials are specified. For more information, the reader can consult Stuart [16].

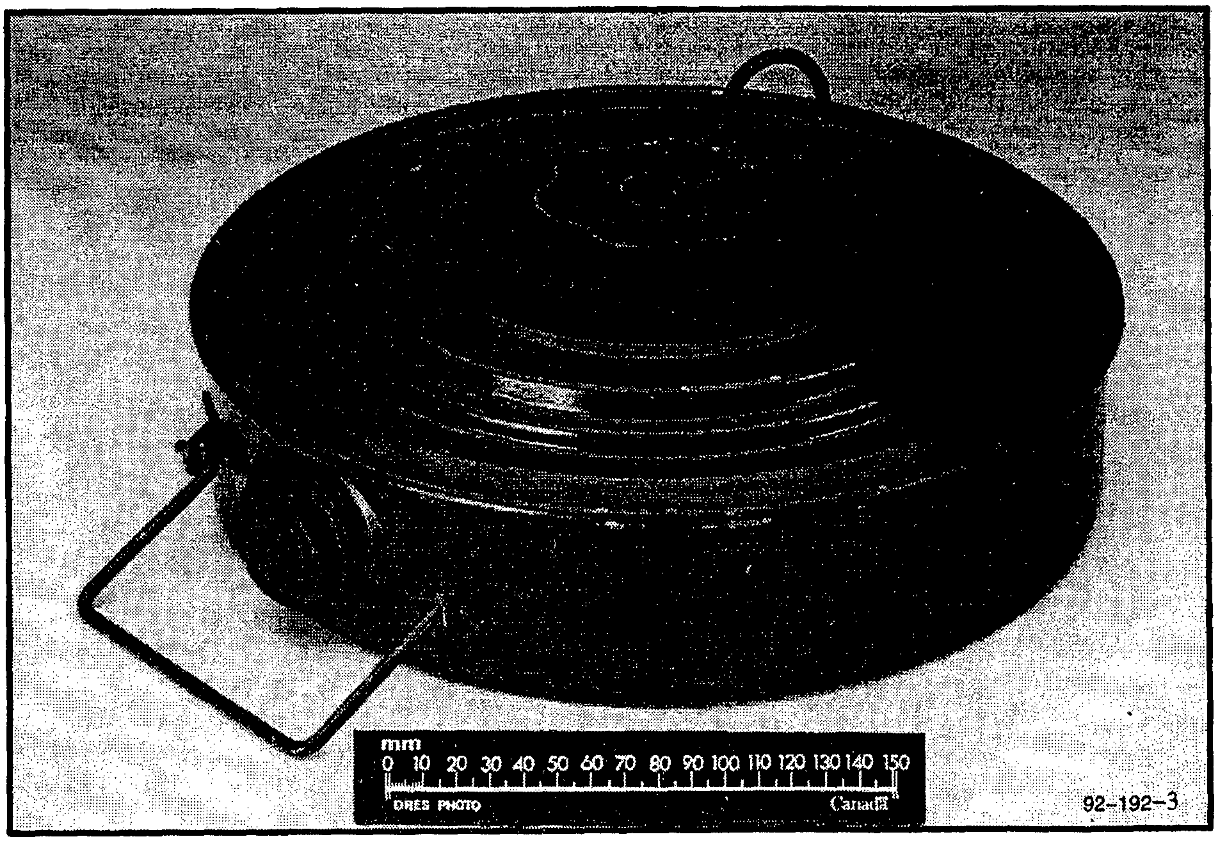

Figure A.1: TMN–46 anti–tank mine. Construction material: metal. Origin: Russian.

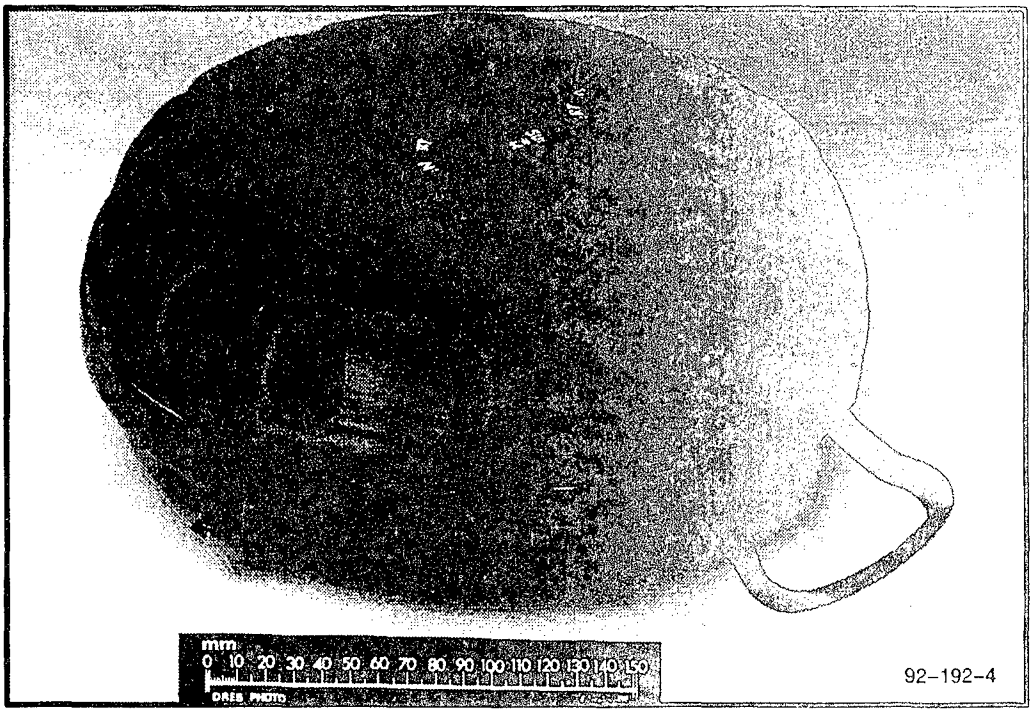

Figure A.2: PM–60 anti–tank mine. Construction material: polymer. Origin: former East German

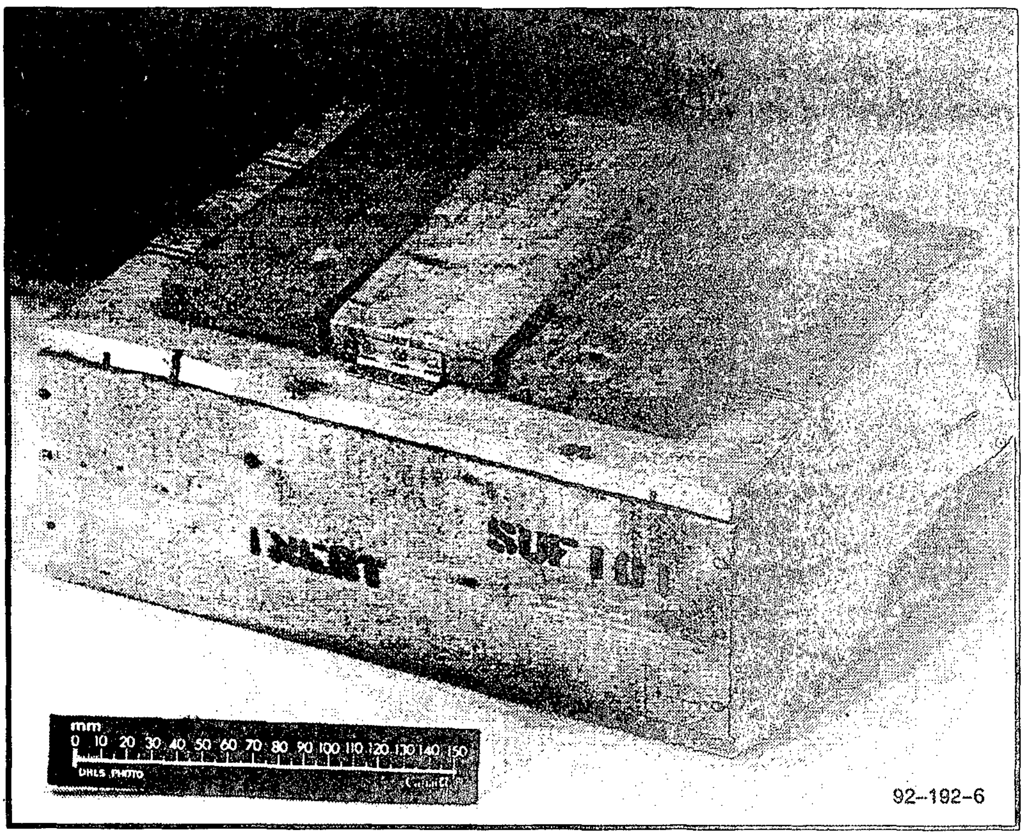

Figure A.3: TMB–D anti–tank mine. Construction material: wood. Origin: Russian.

DOCUMENT CONTROL DATA

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1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.) Defence Research Establishment Suffield	2. SECURITY CLASSIFICATION (overall security classification of the document including special warning terms if applicable) Unclassified

3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title.)

Experimental Evaluation of the Apparent Temperature Contrast Created by Buried Mines as Seen by an IR Imager

4. AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

Simard, Jean-Robert

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The detection of buried mines is a problem of prime interest internationally. One potential method to succeed in this task is to use passive IR imaging to form thermal images of the soil surface. Even though this technique has been intensively investigated for the last 15 years, only few publicly reported studies show quantitative measures of the apparent temperature contrast at the soil surface above buried mines. This document aims to improve this situation. Apparent temperature contrasts are measured for different mine-soil combinations over 24 hour periods with a camera sensitive to long wave infrared (8-12μm). The effect of the variation of burial depth is investigated and special attention is taken to differentiate the thermal effects associated with the soil disturbance from the mine itself. A maximum average of 2 degrees C in apparent thermal contrast is reported and this apparent thermal contrast disappears when the burial depth exceeds 8 cm for the case where the thermal disturbance is related to the buried mine only. A 50% increase (~ 3 degrees C) is observed when the thermal effect of the soil disturbance is present. Furthermore, this last apparent thermal contrast shows little dependency with the burial depth. These results are promising for the detection of mines buried in compacted soil. However, serious reservations about an acceptable false alarm rate and the duration of the thermal effect created by the soil disturbance are expressed.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Buried

Detection

IR

Imaging

Minefield

Mines

Temperature Contrast

DOCUMENT 5

Remote Land Mine (Field) Detection. An Overview of Techniques

ADA 288635

September 1994

Fysisch en Elektronisch Lab Tno
The Hague (Netherlands)

TNO Physics and Electronics
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TN(
Lat
Oude TD
2597 AK The Hag...
P.O. Box 96864
2509 JG The Hague
The Netherlands

Fax +31 70 328 09 61
Phone +31 70 326 42 21

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TNO Defence Research consists of:

MANAGEMENTUITTREKSEL

titel	:	DETECTIE VAN LANDMIJNEN EN MIJNENVELDEN OP AFSTAND, een overzicht van de technieken
auteur(s)	:	Drs. J.S. Groot, Ir. Y.H.L. Janssen
datum	:	september 1994
opdrachtnr.	:	A93KL645/A92KL700
IWP-nr.	:	766.5/767.1
rapportnr.	:	FEL-94-A205

Mijnen vormen een alledaagse dreiging op de moderne gevechtsvelden. Reden hiervoor zijn de hoge kosten-effectiviteit en de mogelijkheid om ze snel te leggen.Tijdens een conflict wordt de doorgang van troepen vertraagd door de aanwezigheid van mijnen(velden). Na afloop van een conflict belemmeren mijnen de wederopbouw van een gemeenschap. Cambodja is een voorbeeld hiervan. In dit land met 5 milljoen inwoners liggen nog 5-10 miljoen mijnen en ongeveer 10 procent van de bevolking heeft verwondingen tengevolge van een mijn. Om het voor militaire bevelhebbers mogelijk te maken om mijnen(velden) te omzeilen, te neutraliseren of te doorbreken is een “real time” detectie systeem voor mijnen of mijnenvelden essentieel.

De basis principes en sterke en zwakke punten van “real time” mijnen detectie met visuele, nabij-infrarode, midden en lange golf infrarode, microgolf radiometrische en radar systemen, worden gepresenteerd in de eerste hoofdstukken van dit rapport.
In het tweede deel van het rapport worden aanbevelingen gegeven voor een toekomstig systeem voor de detectie van mijnen. Deze aanbevelingen zijn gebaseerd op een literatuurstudie, de voornaamste conclusies van de activiteiten en onderzoeksgebieden van de verschillende RSG (AC243 SGE/CET geïnitieerd door panel IX, NAAG AC225) leden (landen) en overleg met en behoeften van DMKL, GEVST-MUN.
De voornaamste aanbeveling is de ontwikkeling van een prototype multi-sensor systeem voor op een voertuig. Dit is gebaseerd op de interesse die de “Genie” toont voor een dergelijk systeem, de kosten van een dergelijk systeem die factoren lager zijn dan voor een systeem dat vanuit een vliegtuig moet opereren en het op betrekkelijk eenvoudige manier kunnen testen en toepassen van sensor fusie. Veelbelovende technieken voor detectie systemen voor op een voertuig zijn:

1. passieve en actieve infrarood beeldvormende systemen,
2. microgolf radiometrie,
3. passieve en actieve visuele en nabij-infrarode discriminatie op basis van verschillen in golflengte afhankelijke reflectie-eigenschappen,
4. radar bodem en vegetatie indringend vermogen.

Voorgestelde tijdstappen in de ontwikkeling van een dergelijk sensor syteem voor op een voertuig zijn: een haalbaarheidsstudie, metingen vanaf een toren en ontwerp, ontwikkeling en het testen van een demonstratiemodel.

EXECUTIVE SUMMARY

title	:	REMOTE LAND MINE(FIELD) DETECTION, an overview of techniques
author(s)	:	J.S. Groot, Y.H.L. Janssen
date	:	September 1994
contract no.	:	A93KL645/A92KL700
IWP no.	:	766.5/767.1
report no.	:	FEL-94-A205

Minefields form a common threat on the modern battlefield. Reasons are the high cost-effectiveness, and the possibility to lay them quickly. During a conflict the passage of troops is delayed by minefields. After a conflict, minefields hamper the development of a community seriously. An example is Cambodia. There are currently 5-10 million mines left in this country with 5 million inhabitants. About 10 percent of the population has mine induced injuries.
To enable military commanders to plan their movements to circumvent the mines (or minefields) or to allocate/employ mine neutralisation/breaching assist to clear a safe route through a minefield, a (near) real time land mine or minefield detection system is essential.

The first chapters of this report present the basic principles and strengths and weaknesses of mine detection of such a system with visual, near infrared, midwave infrared, longwave infrared, microwave radiometric and radar systems.
The second part of the report presents recommendations for future mine detection systems. These recommendations are based on a literature survey, main conclusions from the activities and research of the different RSG (AC243 SGE/CET initiated by panel IX, NAAG AC225) member countries and the discussions and demands of the DMKL, GEVST-MUN.
Main recommendation is the development of a prototype vehicle mounted multi-sensor system since the "Genie" expressed its interest in such a system, it is cheaper than an aircraft mounted system, and sensor fusion can be tested and applied on such a system. Promising techniques for a vehicle mounted detection system are:

1. passive and active infrared imaging,
2. microwave radiometry,
3. passive and active visual and near infrared wavelength discrimination,
4. radar ground and vegetation penetration.

Proposed time steps in the development of a demonstrator of a vehicle mounted mine detection system are a feasibility study, tower measurements and design, construction and testing of a demonstrator.

CONTENTS

1 INTRODUCTION

Minefields form a common threat on the modern battlefield. Reasons are the high cost-effectiveness, and the possibility to lay them quickly, for example from an airplane. During a conflict the passage of troops is delayed by minefields. After a conflict, minefields hamper the development of a community seriously. An example is Cambodia. There are currently 5-10 million mines left in this country with 5 million inhabitants. About 10 percent of the population has mine induced injuries.

NATO member countries recognised the need for a (remote) detection system for mines and minefields and followed a request of the Defence Research Group (DRG), panel IX of the NAAG, AC225 in September 1991. A Special Group of Experts for Combat Engineering Technology (SGE/CET) was established under AC243. The SGE identified two fields of research to pursue: Remote Detection of Minefields (RSG1) and Stand-Off Neutralisation of Minefields (RSG2).
As usual, definitions, objectives etc. of the RSG1 are given in a document called "Terms Of Reference" (TOR). The start of RSG1 was marked by the acceptance of the TOR by the DRG (NATO Defence Research Group) in March 1993. The overall duration of the group will be 4 years. The RSG1 name definition given in the TOR is:

<u>Remote Detection of Minefields</u>:

"procedures and techniques used to locate, classify and report the presence and extent of minefields where the detector system is located separately from the minefield, usually well beyond the lethal range of mines, and where the operator may or may not be located separately from the detector system."

The objective as stated in the TOR is:

"The main objective of this RSG is to investigate the feasibility of a remote minefield detection capability which will enable commanders to plan their movements to circumvent the minefields or to allocate/employ mine neutralisation/breaching assist to clear a safe route through the minefield."

2 HISTORY OF THE PROJECT

Already in 1992 the DMKL ("Directorate of Material of the Royal Netherlands Army") initiated a project (A92KL700) which included the following:

- attendance of the biannual RSG meetings
- literature survey
- basic study of the applicability of mathematical morphological techniques
- initiation of possible follow-up study, based on results of the foregoing parts

The work is carried out by J.S. Groot (TNO-FEL), and is finalised at the end of 1994. Because the expertise of Groot lays mainly in the field of microwave remote sensing, a parallel project (A93KL645) was spawn of which covers the ultra-violet, visual and (thermal) infrared wavelengths. This project led by Y.H.L. Janssen (TNO-FEL) contains:

- basic study of the applicability of UV, visual and active and passive infrared mine detection
- literature survey
- basic experiments and model calculations
- future attendance of biannual RSG meetings concerning close-in detection
- initiation of possible follow-up study, based on results of the foregoing parts

Up till now, four RSG meetings have been attended (December 1992, June and December 1993, June 1994). RSG member countries are Canada (CA), USA, United Kingdom (UK), Germany (GE), Denmark (DK), France (FR), Italy (IT), Belgium (Be) and The Netherlands (NL). These are the main conclusions from the minutes of these meetings by the Netherlands attendant:

- CA, USA, GE and UK have the most comprehensive research programs.
- CA investigated a large subset of possible sensors, but now concentrates on infrared sensors and on image analysis.
- the USA research is oriented towards the development of an operational minefield detection system.
- GE initiated two contracts concerning multi-sensor systems.
- UK's emphasis is on novel microwave sensors.
- DK is in pretty much the same situation as NL, and starts a small research program in 1994.
- CA, UK and DK research is mainly carried out by the national army instead of private companies, which makes co-operation with one of these countries the easiest.
- FR did not yet present their research program, although it is said to have a high priority.
- IT attended only 2 meetings, BE none. Both countries did not present their research programs.

Note that these conclusions are only a subjective interpretation based on what has been told during the RSG meetings, and might not reflect the actual situation accurately.

The TOR objective concerns (near real time) minefield detection during a conflict. This type of detection is thought to be carried out from an UAV (Unmanned Aerial Vehicle), flying at low altitude of typically 100 meter. On ground of the information gathered by the UAV, the commander decides to take an alternative route to avoid, or to clear part of the minefield. NL emphasised the importance of non-real time detection of single mines after conflicts, based on the recent experiences during UN operations (e.g., in Cambodia).

Although close-in detection is not formally part of this RSG's work terrain, sometimes the subject is touched during the meetings. This is due to the overlap between some close-in and remote detection techniques. For example, detection from a vehicle with an infrared camera looking 20 meters forward can be regarded as close-in as well as remote detection. During the June 1994 meeting the question was posed whether certain types of close-in detection should possible become part of this RSG, or should be incorporated in a new RSG. The decision is foreseen to be taken during the December 1994 meeting.

The results of the literature survey are given in the appendices A-H of this report, which include abstracts of the papers and reports read. For reasons of convenience and to be able to use the appendices seperately some abstracts appear in several appendices.

3 IMAGING SENSORS FOR THE DETECTION OF MINES AND MINEFIELDS

The problem of mine and minefield detection is a difficult one, for the following reasons:

- mines are small (5-30 cm diameter)
- mines have a variety of shapes
- mines can be metallic or non-metallic (e.g., plastic or wooden)
- mines can be buried or laid on the surface
- minefields can be patterned or non-patterned

Detection of a single mine is more difficult than that of minefields. In general, un-buried mines are easier to detect than buried ones (not taking into account possible surface disturbances due to the laying process). Similarly, patterned minefield detection will be easier than its non-patterned counterpart. In addition, large mines will be easier to detect than small ones.

Each of the sensors discussed next has its typical strengths and weaknesses with regard to mine(field) detection. The emphasis will be on these characteristics instead of on technical details. A summary of the (dis)advantages of each sensor system is given in table 5.1.

3.1 Radar

References in appendix A related to radar are [A1-A20]. They treat close-in as well as remote detection and buried as well as surface laid mines.

A radar transmits electromagnetic radiation with a wavelength ranging from millimetres (W-band or mm-radar) to meters (P-band radar), or even larger. It receives the radiation back-scattered by objects which intercepted part of the incoming radiation. The amount back-scattered gives the Radar Cross Section (RCS) of the object. The RCS of a mine relative to that of the background determines the detectability of the mine.

The most important radar characteristics are:

- wavelength. Longer wavelengths penetrate (soils) deeper.
- polarisation (transmit and receive antenna polarisation). Conventional radars have a single transmit and receive polarisation. Polarimetric radars act as if they measure with each possible transmit/receive polarisation combination simultaneously.
- spatial resolution. This is the size (in m^2) of the smallest detail which can be resolved by the radar. It always exceeds the wavelength squared.
- radiometric resolution (the smallest change in RCS which is still detectable).

The RCS of a mine (omitting the background) depends on:

- its size. The larger a mine, the higher its RCS (assuming only a change of size, not of wavelength, viewing direction etc.).
- the material it is made from. Metallic mines have generally a higher RCS than non-metallic ones.
- the radar wavelength. The RCS is higher for smaller wavelengths.
- the radar polarisation. The RCS varies quite unpredictable with the polarisation.
- the viewing direction. The higher the mine size to wavelength ratio, the faster the RCS varies with the viewing direction. Cylindrical mines have the highest RCS when viewed from the top or the side (due to specular and two-bounce reflection, respectively).
- spatial resolution, if the resolution is smaller than the mine.

Buried mines have generally a reduced RCS, depending on the depth under the surface (surprisingly, some of the measurement results in [A20] indicate an enhanced RCS).

The *average* RCS of the background depends on:

- the radar spatial resolution ("size of the background"). The larger (worse) this resolution, the higher the background RCS.
- its moisture content. The larger the moisture content, the larger the RCS.
- its surface roughness. Increasing the roughness increases the RCS.
- the radar wavelength. The RCS is higher for smaller wavelengths.
- the radar polarisation. The RCS is smallest for HV, VH, LC-LC and RC-RC polarisation for backgrounds with a near unit scattering matrix (H= Horizontal, V= Vertical, RC= Right Circular, LC= Left Circular). Examples are smooth bare soils and grassland.
- the viewing direction, but in a more or less predictable (smooth) way. It is highest for normal incidence (specular reflection).

Note that the points above determine the *average* RCS of the background. Generally, the measured background RCS varies wildly (in space and time), due to the coherent nature of the radiation transmitted by the radar. For example, the average RCS of a square meter of grass might be 0.1 m^2 but measuring it some time later, or moving the radar "spot" a few meters away might give a value of 0.2, 0.05, 0.28 or ? m^2. This particular phenomenon is known as "speckle", and has noise like characteristics. The amount of variation is precisely known, but can only be suppressed by averaging measurements done at different times or locations. This affects the measurement speed or spatial resolution, respectively speckle is inherent to the use of an instrument which uses coherent radiation, like radar. Moisture and roughness variability in space contribute to the total RCS variation.
Because averaging is inevitable, one should strive for the highest possible resolution, probably below 20 cm. This limits the wavelength below this value, because the resolution can never be better than (be below) the wavelength.

From the dependence of mine and background RCS on the various quantities mentioned, it follows that no single radar will be able to detect all mine types under all circumstances. For example, buried mine detection would require a long wavelength radar due to its ground penetration capability, but this limits its applicability to the largest of mines, because its spatial resolution exceeds the wavelength squared. This in turn increases the minimum background RCS.

Most studies point out that an imaging radar system with the best performance for surface laid mines should have a high frequency (35 or 100 GHz), a spatial resolution smaller than the mine size and be downlooking (i.e., look direction perpendicular to the flat mine tops, which are assumed to be oriented near horizontally). For a real aperture radar (for which the spatial resolution is linearly proportional to the radar-mine distance), this implies that the system should be flown at an altitude below 100 m. The detection probability will depend heavily on background characteristics. The high frequency causes such a system to be useless for buried mine detection. The use of a polarimetric system is recommended, in order to achieve the highest mine-background contrast.

Long wavelength (> 10 cm) radars are able to penetrate the surface to depths at which mines are typically buried, suggesting their utility for buried mine detection. A serious drawback of such a large wavelength is that clutter reduction by spatial averaging is impossible.
However, all literature studied indicated that the detection of buried mines is harder than the detection of the same mines on top of the surface. And even the latter is only possible under the most favourable conditions (small background RCS and high spatial resolution).

3.2 Microwave radiometers

References related to microwave radiometers are presented in appendix B [B1-B11].

As opposed to radar, a radiometer does not transmit radiation. A radiometer receives the natural radiation emitted and reflected by all objects (the former is therefore called an active, the latter a passive system), at a wavelength in the radar range. The amount received gives the radiation temperature T_r. This temperature of a mine relative to that of the background determines the detectability of the mine.

The most important radiometer characteristics are:

- wavelength.
- polarisation (of the receive antenna).
- spatial resolution.
- radiometric resolution (the smallest detectable change of the radiation temperature).

The radiation temperature of a mine (omitting the background) depends on:

- the radiometer wavelength. T_r increases with the wavelength.
- the radiometer polarisation.
- the viewing direction. This depence is weak compared to that of radar measurements.
- the physical temperature of the object. The higher this temperature, the higher T_r.
- the material it is made from. Metal mines have a much smaller T_r than plastic mines.

- the "sky temperature". This is because the radiometer not only receives radiation emitted by the mine, but also radiation reflected from its surroundings, including the sky. This dependence is largest for highly reflective metal mines. The sky temperature depends in turn on cloud occurrence.
- its depth under the ground surface, for buried mines.

The radiation temperature of a background depends on:

- soil moisture. T_r decreases with increasing moisture.
- soil roughness. T_r increases with increasing roughness.
- radiometer wavelength. T_r increases with increasing wavelength.
- radiometer polarisation. It is higher for vertical than for horizontal polarisation.
- incidence angle (angle between viewing direction and the vertical). For incidence angles below 30 degrees the dependence is small.

The measured T_r of a mine in a background depends on the beamfill factor, which is the mine area divided by the spatial resolution. The larger this beamfill factor, the larger the difference (= contrast temperature) between T_r and the background only radiation temperature.

As opposed to radar, radiometer measurements do not suffer from "speckle". However, because the natural radiation emitted is essentially noise, one has to use a large bandwidth and integration time to achieve a sufficient high radiometric resolution.

Ref.[B8] presents measurements at 35 and 90 GHz (86 and 33 mm wavelength, respectively) performed with a scanning vertically polarised radiometer, operated from a roof (Figure 3.1). The next results and figures are copied from this reference.

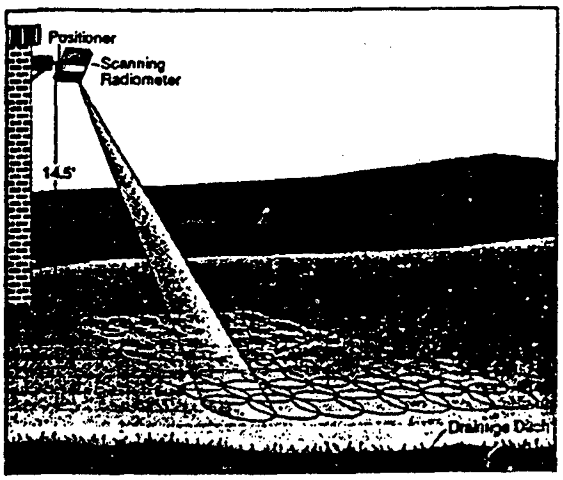


Figure 3.1: A sketch of the experimental set-up.

Figure 3.2 shows two consecutive scans over a metallic mine (located at scan angle of 0 deg.), clearly proving its detectability. The difference between the two is due to the limited calibration accuracy. The contrast temperature T_C is approximately 270 K - 50 K = 220 K for this particular case.

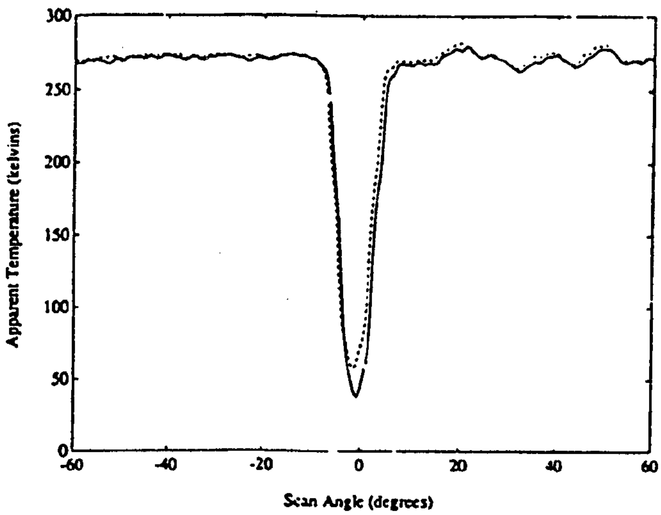


Figure 3.2: Two consecutive scans at 90 GHz.

Figure 3.3 shows T_C of a metallic target as a function of look angle (= 90 degrees - incidence angle).

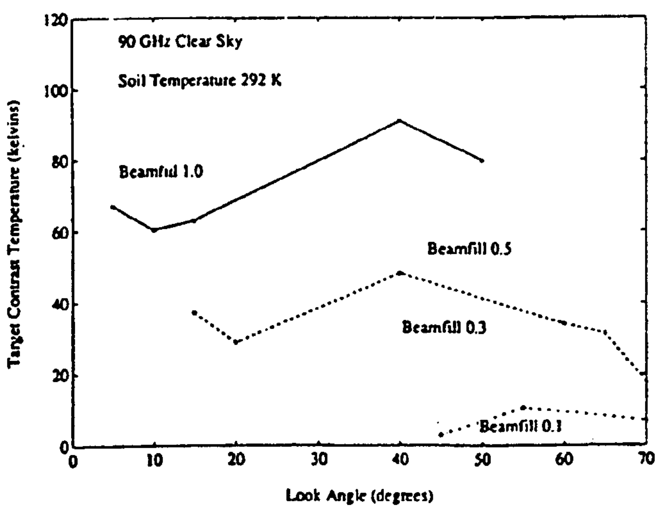


Figure 3.3: Metallic target contrast as function of look angle for constant beamfill factor.

T_C depends only moderately on the look angle. As noted before, the contrast temperature depends on the beamfill factor. Figure 3.4 presents data on the relation between the beamfill factor and the contrast temperature, in conjunction with an antenna model fit. This graph proves that detection is possible (the contrast temperature exceeds a few degrees Kelvin), even if the mine is smaller than the spatial resolution (beamfill factor below 1).

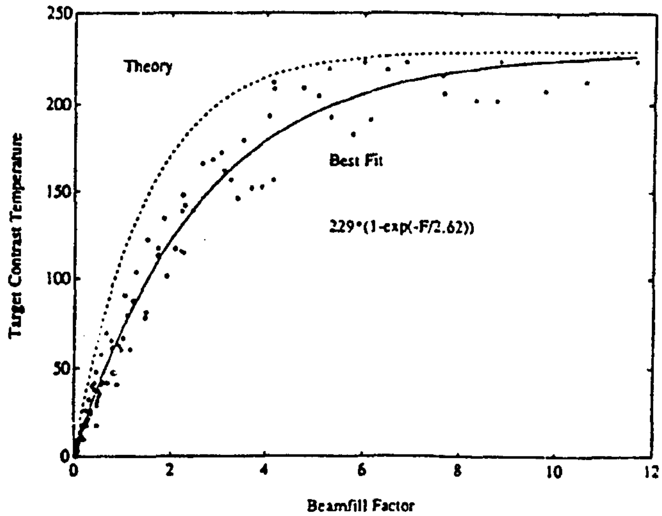


Figure 3.4: *Metallic target contrast temperature from the Gaussian antenna model compared with the 90 GHz clear sky data. The dashed line is the Gaussian model and the solidline is the best fit.*

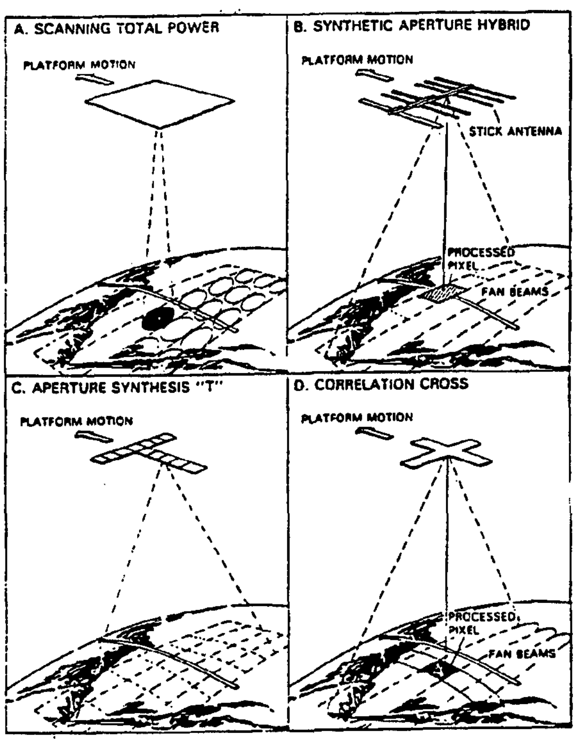


Figure 3.5: *The panels illustrate several different imaging radiometers: (a) A scanning total power radiometer; (b) A hybrid which achieves resolution along track with a real aperture and uses aperture synthesis to obtain resolution across track; (c) A radiometer which employs aperture synthesis in both dimensions with the antennas arranged along the arms of a "T"; and (d) A radiometer in which the scene is mapped by correlating the beams formed by each arm of a "cross" (from [B11]).*

From this study it is clear that metallic objects which are not obscured by vegetation or any other covering are readily detectable. The system recommendations done in this report on ground of the measurements are that a helicopter based system resembling the roof based one is feasible. Key parameters are: frequency 90 GHz, antenna diameter 30 cm, nadir spatial resolution 0.4 m^2, radiometric resolution 1 K, flying height 15.2 m, nadir swath width 50 m, flight speed 30 km/hr and a weight of 70 kg.

It would be interesting to investigate the use of a synthetic aperture antenna like that of [B10-B11]. Figure 3.5a illustrates the principle of image formation by a real aperture system, like the helicopter based one above. The image is formed by cross-track scanning, and the movement of the platform. By using a synthetic aperture antenna like that of figure 3.5c, one doesn't need to scan cross-track like in figure 3.5a. The T-shaped antenna consists of several (small) antennas. Image formation is accomplished by processing the data from different antenna pairs with different spacing. The highest (best) spatial resolution is approximately the same as that of an antenna with equal physical dimensions. However, because the T-shaped antenna array is completely filled with antenna's, it will be lighter (this is especially advantageous for operation from space). A drawback is that the radiometric resolution drops because of the reduced physical collecting area (sum of the individual real apertures). It can be shown that this resolution is nevertheless only marginally worse than that of a real aperture system, because the synthetic aperture system does not scan [B11]. This increases the integration time. Note that unlike the SAR case, a radiometer's synthetic aperture does not exceed the physical antenna size.

3.3 Visual and near infrared

References related to detection of mines with visual and near infrared systems are presented in appendix C [C1-C10].

A covert, all day, all weather, real time sensor is required for detection of mines and minefields. The visible and near-infrared (NIR) wavelength range does not always fulfil these conditions since:

- passive imagers in these wavelength bands can only be used during day-time
- mines are more easy to camouflage (e.g. with paints) in these wavelength ranges
- the transmittance in these ranges is often poor compared to transmittance in other wavelength ranges

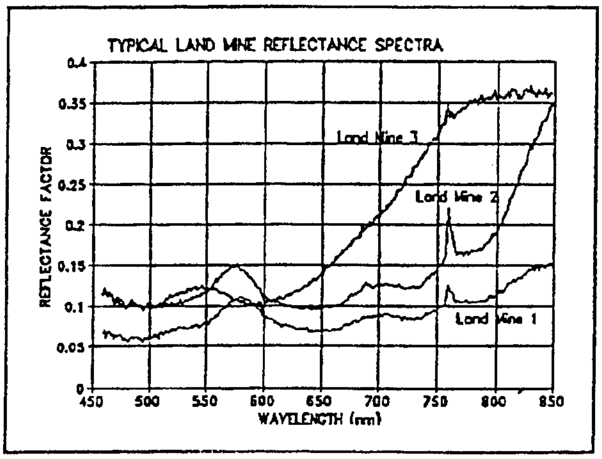
Nevertheless, detection in the visual and NIR bands has also several advantages [C7]:

- it can be done passive
- these sensor systems have often a high spatial resolution and visible texture
- most systems are real time
- it is a mature technology
- the sensors are often low cost compared to sensors active in other bands
- the sensors are often compact compared to sensors active in other bands

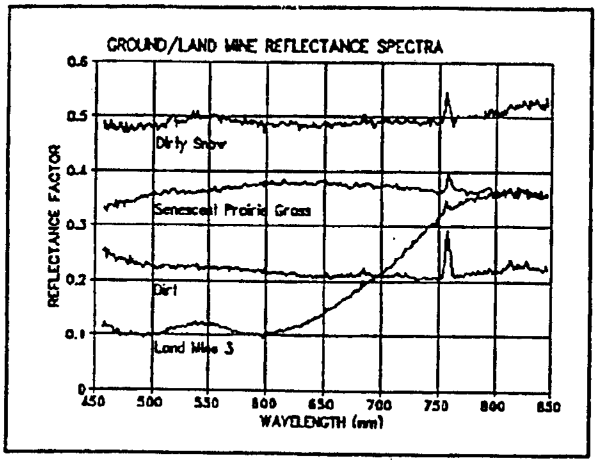
Because of these advantages most future mine detection systems will consist of a sensor active in the visible and NIR band, complementing a sensor active in another band. Potential visual and NIR imagers are 8- and 12 bits linear CCD (Charge Coupled Devices) cameras, active NIR laser scanners, and LLLTV (Low Light Level Television). These different potential systems and aerial photography are discussed separately in the following section.

<u>8- or 12 bits linear CCD camera, possibly combined with several spectral filters:</u>

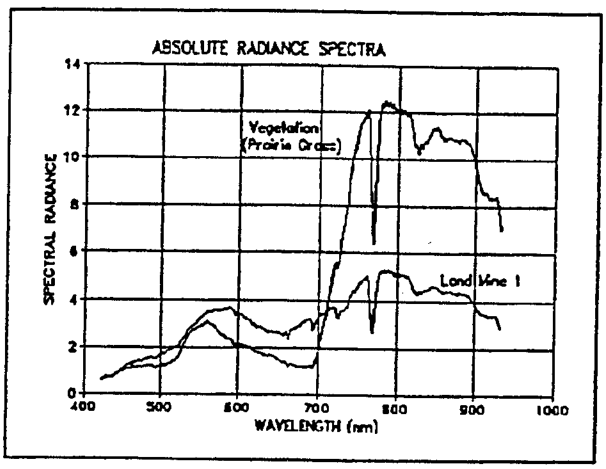
In the visible (wavelength range: 400-700 nm) and NIR (700-1300 nm), mines are often camouflaged with paints, but exact spectral matches occur only at a few points in the spectrum. Bands where large differences in reflectivity occur vary in centre position and width for different mines, mine paints and background types. Figure 3.6 presents vegetation and land mine spectra.



(a)



(b)



(c)

Figure 3.6: (a) typical land mine spectra, (b) typical ground/land mine reflectance spectra, (c) absolute radiance spectra.

Although these spectra show many similarities, such as a green reflection peak (at 550 nm), a red reflection dip (at 680 nm due to the absorption by chlorophyl) and an increased signal in the NIR, there are many differences that could be used for future analysis.
Overall vegetation spectra exhibit a much more pronounced absorption in the red (680 nm) with a sharp corner (700-730 nm) where the signal begins to strengthen in the NIR, as can be seen in figure 3.6c. The signal also becomes much more pronounced in the NIR vegetation spectra than the land mine spectrum. From [C10] it follows that five broad wavelength ranges are sufficient to determine differences between spectral data of mines (also camouflaged and painted) and backgrounds. These conclusions are based on spectral data of 11 minerals, 4 types of rocks, 5 types of soil, 33 types of vegetation and 5 types of mines. The resulting wavelength bands are:

- 0.596 - 0.732 μm
- 0.734 - 1.238 μm
- 1.502 - 1.750 μm
- 1.998 - 2.130 μm
- 2.134 - 2.290 μm

From [C9] and [C10] it follows that it would be interesting to investigate the possibility of mine and minefield detection with an 8 bits CCD-camera or a 12 bits linear CCD in combination with several band filters (visual and NIR). An advantage of such a system is that it gives real time images (and detections), that it is relatively low cost, passive and has a high spatial resolution.

Active NIR scanner:

The image of an active NIR scanner shows the retro-reflected NIR radiation that is generated by a source on that same system itself or another man-made source. Often a laser is used as the radiation source, but active illumination with a lamp is also possible.
Advantages of an active NIR laser scanner are:

- a high spatial resolution,
- construction of 3D images possible: information on the distance between the imagers and the object is measured,
- can be used during day as well as night time,
- no image clutter due to shadow,
- it can be side- or down-looking,
- large area coverage.

Disadvantages of active NIR laser imaging system are the speckle in the images and the operating problems with a moving platform e.g. a vehicle or airplane.
Recent developments show that these problems can be reduced to an acceptable level. Together with the above mentioned advantages it is clear that an active NIR laser scanner is a promising technique for the detection of mines and minefields. Still, a lot of research has to be done in this field. Bi-directional reflectance data of mines have to be collected. Of equal importance is knowledge of military paints. Experiments should investigate different mine shapes and

textures, the effects of water or dirt on mine surfaces, and the visual and NIR reflectance and statistical distribution of various materials within the natural environment.

Low Light Level Television (LLLTV):

Another possibility of the usage of the visible and NIR wavelength band is by means of LLLTV. An advantage of these systems is that they can be used during night time. A disadvantage of these systems is that they generally have a poor discrimination compared to for example thermal infrared imagers and that the discrimination decreases with decreasing intensity of the light. Therefore these systems are less suited for the detection of mines and minefields.

Aerial photography:

Conventional aerial photography will continue to have important applications with respect to detailed mapping of minefields. However, a serious drawback is the absence of a digital output.

3.4 Mid-wave and long-wave infrared

References in appendix D [D1-D20] relate to mine detection in the mid-wave (MWIR) 3-5 μm band and the long-wave (LWIR) 8-12 μm band. Close-in detection as well as remote detection and surface laid and buried mines are treated in these references.

Figure 3.7 illustrates the major features of energy transport from the scene to the IR imager. Scene radiation along a line of sight (LOS) from the source to the imaging system arises from four mechanisms:

- self emission,
- transmission of emissions from objects behind the source,
- reflection of remote emissions from objects in front of the source,
- scattering and/or diffraction of all these from outside the LOS into the LOS by the intervening atmosphere.

All these phenomena are angular dependent, so that the IR appearance of a differential element of a source's surface may depend on the viewing angle relative to the surface normal and on the angles of external sources relative to the surface normal.

The infrared contrast of natural terrain features and man-made objects as mines is strongly dependent on the strength of insolation. In an infrared image the contrast (e.g. between a mine and it's background) is specified by the apparent temperature difference between the source (e.g. mine) to the apparent temperature of its background (e.g. soil).

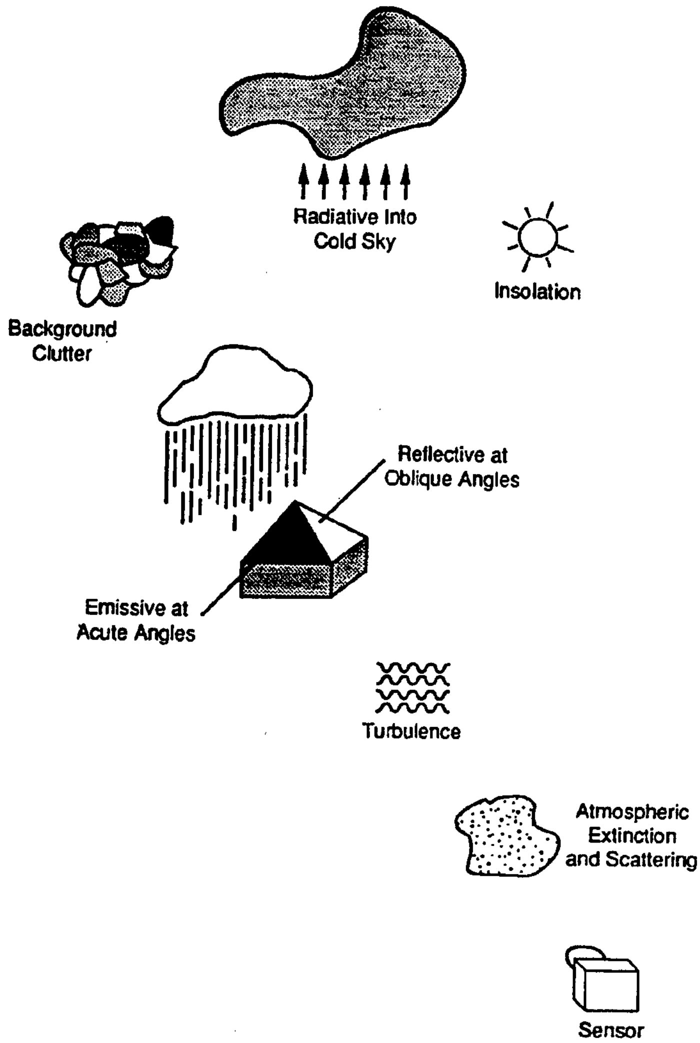


Figure 3.7: *IR imaging characteristics [D18].*

Due to atmospheric conditions (figure 3.8) and sensor capabilities the MIR wavelength band is divided into two bands, the MWIR 3-5 μm band and the LWIR 8-12 μm band.

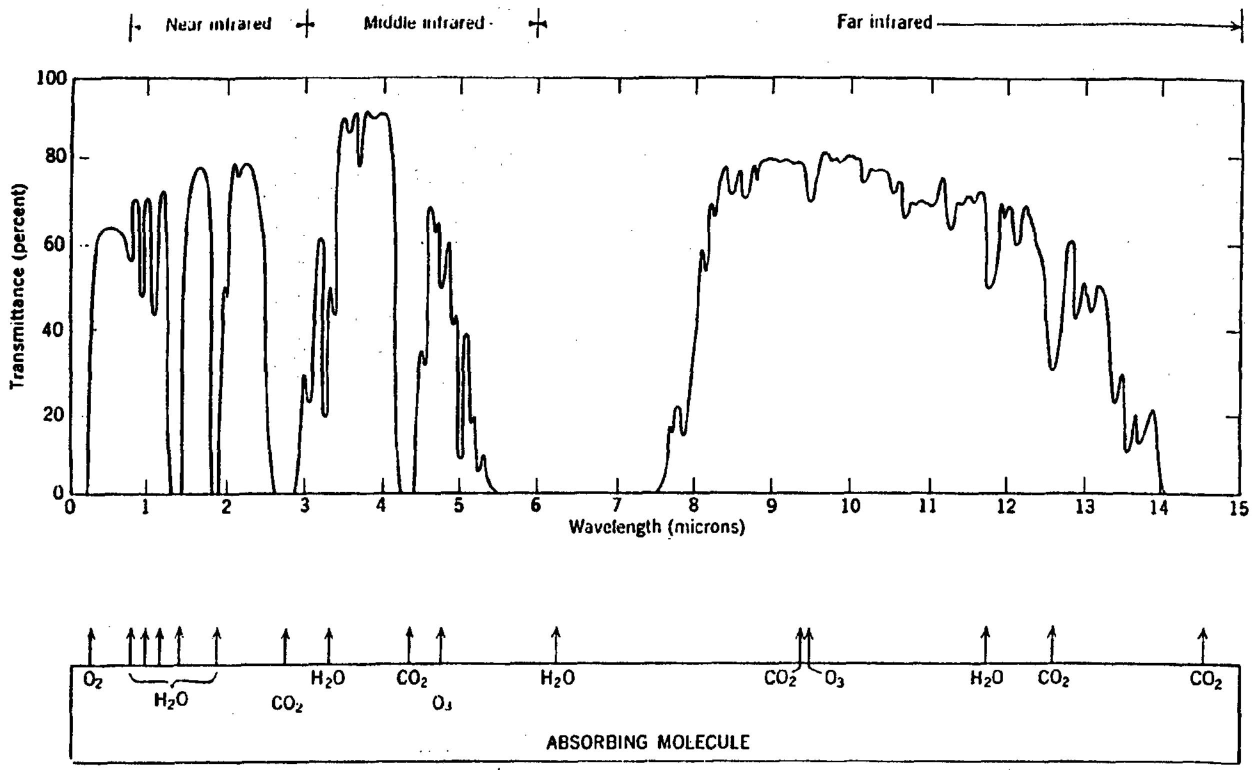


Figure 3.8: transmittance of the atmosphere for a 6000 ft horizontal path at sea level containing 17 mm of precipitable water.

Good performing IR imaging systems can be divided into two main categories: IRLS (Infrared Line Scanning) systems and FLIR (Forward Looking Infrared) systems.
An IRLS system is an imaging device that forms images by successive scans of a rotating mirror. The scans are transverse to the line of flight or drive of the vehicle carrying the IRLS. The second scan needed for a two-dimensional image is provided by forward motion of the vehicle. A for mine and minefield detection very useful type of a IRLS is a pushbroom scanner [D19]. If a vertical scanning mechanism is added to the IRLS a form a FLIR system is created.
FLIR systems [D20] are commonly divided into two broad categories: scanning and staring. For the staring FLIR systems often Focal Plane Arrays (FPA) are used. Such an FPA is a detector array of e.g. 480 x 640 detectors. In general, the larger the number of detectors, the higher the sensitivity and the smaller the minimum detectable contrast of the thermal imager. The high sensor sensitivity is ideal for the detection of mines, as can be seen in figure 3.9.

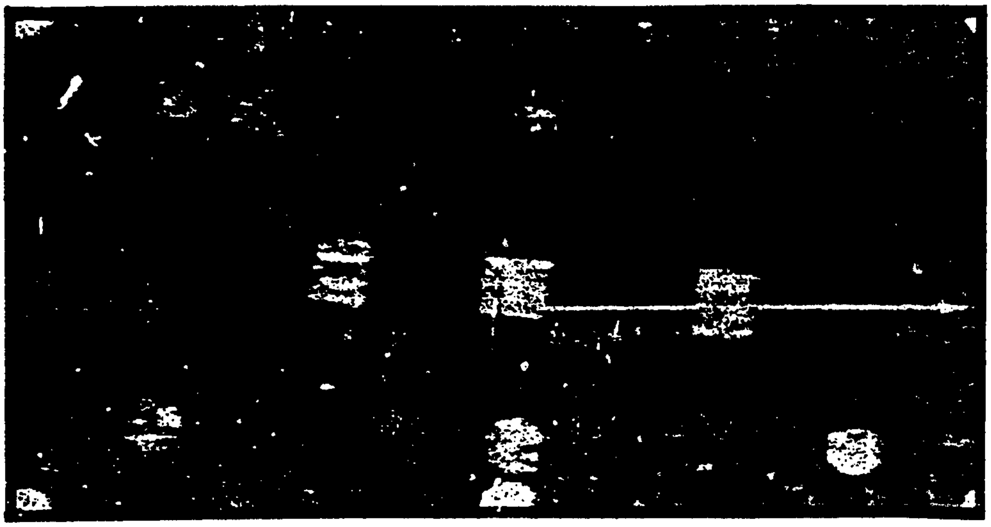


Figure 3.9: Active IR image of PM-60 and TMB-D mines on a soil background [D15].

Apart from the division of IR systems in IRLS's and FLIR's one can divide them in active and passive systems. Active IR systems obtain an image of a scene by measuring the exact reflected IR radiation which was generated by an emitting source on that same system itself. This principle is called retro-reflectance. A well known and good performing active MIR system is a high resolution CO_2 laser system with a nominal wavelength of 10.6 µm.
A passive IR system does not use such an emitting source on the system and creates an image that is only formed by the factors shown in figure 3.7.
Differences, advantages and disadvantages of active and passive IR systems are presented in table 3.11.

Detection of a mine or mines depends on:

In case of passive sensors:

- the difference in apparent temperature between a mine and its background. The apparent temperature is a combination of the emission and reflection of the TIR radiation and is determined by the heat balance of that certain element. The apparent temperature depends on material parameters e.g. reflection coefficient and environmental and meteorological conditions as sun illuminance, relative humidity and environmental temperature. Due to the heat exchange of the earth's surfaces and the atmosphere, twice per day a thermal "washout" (minimum contrast between mines and their backgrounds) may occur. Optimal passive TIR detection of mines times should be done on a time of day where the thermal contrasts are high. Nevertheless, the period of a day that a thermal "washout" appears becomes much smaller due to the good performance of modern TIR camera's. It is already possible to detect very small temperature differences, IR imagers with FPA's can have NETD's (Noise Equivalent Temperature Differences) of up to 0.03 °C.

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- The spatial resolution: the IFOV (Instantaneous Field Of View) of a passive TIR camera should at most cover the size of a mine. For example detection of a 30 cm mine obligates use of a sensor syetm with a spatial resolution of less than 30 cm. For a system with a FPA it is possible to detect mines of approximately 5 cm at a distance of 500 meters. Typical IFOV's of a system with a FPA are .2 mrad.
- Clutter: detection of a mine or mines with a passive TIR imager not only depends on the IFOV and NETD of that imager but also on the clutter in the background. Mines in an uncluttered background are much more easy to detect then mines in a highly cluttered background. Clutter is a complex phenomenon and depends largely on the spatial distribution of the background, which depends on e.g. the variation in soil , soil type, moisture content, rocks, vegetation, shadows, and illumination.
- Atmosphere: the propagation of radiation and therefore detectibility of mines depends on the atmospheric transmittance. Transmission will decrease with increasing distance, due to increasing scattering as well as increasing absorption. For small distances (e.g. 500 meters) the transmission losses in the IR are relatively small.

In case of active sensors:

- For active IR sensors instead of he apparent temperature, the difference in retro-reflectance of a mine and its background is important. The IR reflectance of a mine depends on its surface conditions (e.g. roughness), material properties (reflection coefficient) and orientation (e.g. sloping or flat). For example (not painted) metal mines can create strong retro-reflections and non-metal mines with a rough (diffuse) surface structure can be hard to detect.

- The effect of spatial resolution on the detectibility is almost the same as for passive IR systems, except that the laser-spot that is used can be smaller than the IFOV of the IR imager.
- Overall, images of active systems show less clutter then images of passive system. One of the reasons of this is that in images of active IR systems there is no clutter due to shadows because of the retro-reflectance principle of such a system. Of course also the spatial distribution of the retro-reflectance image is different from that of an image of a passive system due to the difference in illumination.
- Images of an active IR system show speckle. Speckle arises from the reflection of coherent illumination from a diffuse surface. The diffuse surface of e.g. a mine creates an array of scatterers that is independent and randomly phased. This results in contructive (bright spots) and destructive (dark spots) interference at the observation plane. As can be seen in figure 3.9, this speckle can have a large influence on the detectibility of mines and minefields.
- The effects of the atmosphere on the detection of mines is for active sensors almost the same as for passive sensors.

Table 3.11: Differences, advantages and disadvantages of active and passive TIR imaging systems for remote mine (field) detection.

	PASSIVE thermal infrared system	ACTIVE infrared system
principle:	image of scene constructed of TIR emission and reflection of the scene	image of scene constructed of retro-reflectance of the radiation of a source on the system
contrast between mine and background:	difference in apparent temperature between mine and background	difference in angular reflectance between mine and background
contrast behaviour:	contrast varies mainly due to sun illuminance, meteorological and environmental conditions	contrast between a mine and the background is constant
most common wavelength band:	MWIR, 3-5 μm LWIR, 8-12 μm	10.6 μm (CO_2 laser)
image distortion:	clutter	speckle
vulnerability:	less	greater due to complexity, possi-bility of jamming the data link
countermeasures:	more difficult: - paints: anti-reflective - modifying shapes - decoys	less difficult: - paints: anti-reflective - rough surface - changing surface orientation - decoy

Both active and passive IR systems have limitations in terms of their applications to mine and minefield detection. A system which simultaneously creates active and passive IR images would be vastly superior to either of the two individual methods.

4 SIGNAL PROCESSING TECHNIQUES

Most of the data techniques that are presented in this chapter are a summary of the techniques presented in a book on image analysis [F25], a Danish paper [F5] and some articles on morphology [F8-F24], and focus on the techniques applicable to autonomous detection of mines and minefields.

Image analysis is a multifaceted subject that deals with sensors, data analysis algorithms, dedicated processing hardware and storage devices. This chapter deals with the subject of data analysis algorithms. The purpose here is to cover the most important elements of data analysis tasks towards mine(field) detection. The principle stages involved can be categorised as:

- image enhancement
- edge detection
- segmentation
- feature extraction and classification
- morphology

The first four topics are grouped together in paragraph 4.1 since they serve as a building block for image analysis on mine detection. Morphology is treated as stand alone topic covered in paragraph 4.2.

Mines are assumed to be distributed in regular patterns, and sensors are assumed capable of creating low contrast images of a limited percentage of mines. There is no restriction on the particular kind of sensor, except that it must have an imaging capacity. It is however recognised that the particular choice of a sensor will in general have an impact on the choice of data-processing algorithm.

4.1 Image enhancement, edge detection, segmentation, feature extraction and classification

Enhancement:

The purpose of image enhancement is to improve image quality by employing techniques that suppress noise, de-blur object boundaries and highlight some specific features within images. Image enhancement tools help simplify those operations that normally follow the image enhancement step. Image enhancemet is also used for image processing applications in order to enhance the image appearance. For real time detection of mines by men (instead of automatic mine detection), enhancement techniques are very useful since they improve visualisation and image display.

Edge detection:

Information content in the edges of an image can reveal important object characteristics such as size and shape. Most edge detection techniques employ some type of gradient measure. Edge detection techniques for mines can very from simple models to more complex stochastic-based edge detection models. Examples of edge detection filters for mine detection are [F5]:

- gated filtering: this method is based on mean contrast difference in a variable region surrounding the targets. The result of the algorithm produces images which contains the contrast difference between the mean value of the pixel intensity in the inner window and the mean value of the intensity of the surrounding pixels in the outer window.
- local filter operator: this operator is flexible with respect to accentuating different features in images, which occurs for mines covering a small region in an image.
- inverse median filter: the general method is to replace the grey level of each pixel by the median of the grey levels in the surrounding region of pixels. This filter is particularly efficient when the noise pattern consists of strong, spikelike components, and preserves edges.
- contrast filter: with a contrast filter edges, lines (e.g. roads) as well as homogeneous areas can be suppressed.

Segmentation:

Image segmentation, the process of partitioning a digital image into regions, is important for the recognition of mines and mine-types. There are various segmentation algorithms that can classify a group of pixels with similar image properties into a mine. These can be grouped into three main categories:

- thresholding,
- edge detection,
- region growing.

Some of the above techniques are referred to as "bottom up" techniques in the sense that the image segmentation process relies on the individual grey values of pixels without using any knowledge of spatial relationships (of e.g. mines) between various structures in the image. In contrast to "bottom up techniques", "top down" methods use information about the shape and position of regions of interest to guide the image segmentation process.

Feature extraction:

Feature extraction is one of the essential steps that follow image segmentation. Typical features for mine detection can be shape, area, colour and texture. These features can be used to classify patterns (minefield), recognise shapes (mines) or seperate suspect parts from good parts. Features can be defined to be local, global or both. Features based on only local image data can produce poor results due to image noise and poor image contrast.

4.2 Mathematical morphology

Mathematical morphology is the name for a number of image processing functions based on set theory. The fundamental theory is developed in the sixties. This theory was applicable to binary images (black-and-white images) only. It was extended for use with grey-scale images in the eighties. The (thermal infrared, radar, ...) images foreseen to be used for minefield detection are all grey-scale images: these images contain the emission, reflection, ... as a function of position. In the past the use of dedicated parallel hardware was obligatory in order to run the algorithms in a reasonable amount of time. Recently efficient sequential implementations were made, which execute fast on ordinary hardware (e.g., SUN workstations).

The most important applications of the algorithms regard:

- identification of geometrical structures (e.g., locating all circular disks).
- segmentation (e.g., splitting an image in sub-images which have approximately constant brightness).
- image enhancement (e.g., of edges as in figure 4.1).
- hierarchical decomposition (splitting an image in a set of images which represent the same information at different resolutions).

Figure 4.1: *The image to the right results from applying the morphological gradient operator (which enhances edges) to the image at the left [F16].*

To get an impression of the use of the morphological algorithms for mine(field) detection we:

- performed a small literature survey. Abstracts on this topic are in appendix F [F8-F24] of this report.
- requested for the tape with thermal imagery of a test minefield offered by Dr. R. Barnard (Fort Belvoir, chairman of RSG-1) during the December 1993 RSG-1 meeting. We got this during the June 1994 meeting.
- installed the implementation of grey-scale morphological algorithms by A. Peter's (Vanderbilt University School of Engineering, Nashville) on a SUN workstation. The algorithms will be tested on the above mentioned thermal imagery.
- made a program which creates rudimentary radar images, consisting of several geometrical shapes (block, cone, pyramid) with additive or multiplivative ("speckle") noise superimposed on it. These images were used to get an impression of what the morphological algorithms do exactly.

4.3 Minefield detection

The detection of minefields is different from the detection of separate mines. Research in UK showed that the detection of only a small amount (e.g. 40 %) of the mines in a minefield is enough to detect a minefield. The approach for the detection of minefields consists of three basic steps.

1. Initially thresholded *mine (e.g. edge) detection* filters are applied to the image data, to provide a set of candidate targets.
2. With the candidate targets, *complex geometric* structures are built by analysing the context of each candidate targets. Based on the complex structures, a target location hypothesis is constructed.
3. The input image is re-examined with the mine-detector, where the parameters are modified properly. If the target hypothesis is confirmed, the candidate target set is expanded and the procedure continues until a new target hypothesis cannot be established.

Techniques for the above points 1 and 3 are described in paragraph 4.1.

<u>Complex geometric shapes extraction:</u>

Complex shapes are characterised by geometric features. The first step is thus to provide an internal low level representation of the geometry. The next step is to formulate a hypothesis about the underlying structure of the target distribution and to test the hypothesis for confirmation or rejection.
Several methods like line building, syntactic parsing, regular array detection are already known in literature. These methods are complex, but can function well if the quality of the input image is well enough. Good examples of these methods are described in [F3, F4, F6, F7].

5 RECOMMENDATIONS

A (near) real time land mine or minefield detection capability is essential since it will enable military commanders to plan their movements to circumvent the mines (or minefields) or to allocate/employ mine neutralisation/ breaching assist to clear a safe route through the minefield.

The military benefits will include the following:

- fast mine and minefield detection
- reduced casualties and less equipment loss
- advanced planning for mine and minefield avoidance or breaches
- enhanced mobility

Results of the in chapter 3 represented (dis)advantages of imaging mine detection systems in several wave-length bands are summarised in table 5.1.

The recommendations presented in this chapter can be seen as a guideline for the initiation of possible follow-up studies. They are based on the literature survey, the main conclusions from the activities and research of the different RSG member countries and the discussions and demands of the DMKL, GEVST-MUN (project leader ing. N.L.P. de Bruyn Prince-van Kempen).

<u>Recommendations on remote mine detection:</u>

1. RADAR:
   The literature survey and experimental results of several member countries of the RSG indicate that conventional medium-resolution imaging radars are less suitable for remote mine detection. Probably detection of the largest (30 cm diameter) mines becomes possible for spatial resolutions below 5 cm, for certain aspect angles. The ground penetrating capability of long wavelengths makes radar one of the few candidates for buried mine detection. Characteristics and results of existing systems (e.g., which are currently used to locate buried pipe lines) should be investigated with respect to their applicability to buried mine detection.

2. MICROWAVE RADIOMETRY:
   Recent research shows that this detection principle is promising for remote mine detection. None of the RSG members are currently investigating this field, due to budgetary reasons. Research of TNO-FEL on this technique [B10-B11] would be a welcome addition to the RSG's workprogram Therefore a feasibility study at the costs, characteristics, possible applications and detection chances is recommended. This feasibility study should include measurements with a tower-based system.

Table 5.1: (Dis)advantages of imaging systems in several wavelength bands.

sensor: class	sensor: type	sensor: wavelength	all day[1]	weather restrictions[2]	spatial resolution[2]	non-metallic more difficult[3] ?	vegetation/ ground penetration[4]	counter measures	speckle/ clutter/ shadows/ noise	real time ?	mine aspect angle dependence	system dimensions[5]
visual & NIR	lineair CCD with spectral filters	0.596-0.732 μm 0.734-1.238 μm 1.502-1.750 μm 1.998-2.130 μm 2.134-2.290 μm	no	rain, fog, etc.	adequate	no	none	difficult	clutter due to shadows	yes	medium	small
	active NIR laser scanner	0.6943 μm[6], 1.064 μm[7], 1.54 μm[8], 1.543 μm[9], etc.			adequate	no	none	possible with jammer	speckle noise	yes	large	small
	LLLTV	400-800 nm	yes	idem	adequate	no	none	easy (paints)	clutter due to shadows and high noise level	yes	medium	small
	aerial photography	400 nm - 1.1 μm	no	idem	adequate	no	none	idem	clutter due to shadows	no	medium	small
infrared: MWIR & LWIR	passive	3-5 μm 8-12 μm	yes	heavy rain and fog, etc.	adequate	yes	poor	difficult	clutter depends on weather conditions *)	yes	small	small
	active	10.59 μm[10], etc.	yes	idem	adequate	yes	none	possible with jammer	speckle noise	yes	medium	medium
microwave	radar	30 cm	yes	none	inadequate	yes	good	idem	idem	yes, but expensive	medium	large
		3 cm	yes	none	doubtful	yes	poor	idem	idem	idem	large	medium
		3 mm	yes	none	adequate	yes	none	idem	idem	idem	large	medium
	radiometer	3 mm	yes	none	adequate	yes	none	difficult	thermal noise, clutter as *)	yes	small	small/ medium

1 all day means day- as well as nighttime operation possible
2 assumptions: distance between mine and sensor system = 100 m, mine diameter = 15 cm
3 with respect to metallic mine detection
4 mine depth of 10 cm assumed for ground penetration
5 small < 50 cm x 50 cm x 50 cm < medium < 1 m x 1 m x 1 m < large
6 Ruby
7 Nd:YAG
8 Er:Glass
9 Raman-Shifted Nd:YAG
10 CO_2

3. VISUAL and NEAR INFRARED:
The characteristics of visual and near infrared imaging are often requested as addition to an imaging system active in another wavelength band. This is because imaging systems in these bands are often low cost, compact, have a high spatial resolution and can be used real time. Using these systems in combination with several well chosen spectral bands, makes is possible to even detect camouflaged, partly covered mines. A recommendation for a future follow-up is a feasibility study at the possibility of the addition of a visual and near infrared imaging system (for example a 12 bits CCD line-scanner with several filters) to another mine detection system.

4. MID-WAVE and LONG-WAVE INFRARED:
Recent research of the RSG member countries and literature survey show that the mid- or long-wave infrared wavelength band is a promising band for remote mine detection. An active thermal infrared system as well as a passive thermal infrared system have several advantages compared to those operating in other wavelength bands and most of these disadvantages can be abolished by a combination of an active and passive system. Therefore a feasibility study into a combined passive and active remote mine detection system is strongly recommended. This feasibility study should include measurements with a tower-based system.

5. SENSOR FUSION:
Shortcomings of individual wavelength bands can be reduced by combining several wavelength bands. Meteorological conditions (such as rain showers) can make mine and minefield detection in mid- and longwave infrared wavelength bands difficult. Small mines are hard to detect with a system based on radar or microwave radiometry. Detection systems that use CCD camera's active in the visual and near infrared wavelength ranges can not be used during night time. A mine(field) detection system utilizing several wavelength bands simultaneously will circumvent part or even all of these shortcomings. Therefore in future research the above mentioned feasibility studies should be combined in a way that their results can be compared and can lead to an advise on a multispectral mine(field) detection system.

6. IMAGE PROCESSING:
Even as important as a future mine detection system is the interpretation of the data of such a system. A study on the best processing techniques and a reliable and accurate interpretation of the images of a remote mine detection system has to run parallel with the development of a mine(field) detection system. Some examples of of processing techniques were presented in chapter 3.

7. FUTURE RESEARCH: The research in the Netherlands should have as main long term objective the development of a demonstrator vehicle mounted multi-sensor system. Table 5.2 provides a provisional time table for the different steps leading to such a system. Reasons for the choice of a vehicle mounted instead of a UAV based system are:
   - the "Genie" expressed its interest for a vehicle based system.

- a vehicle based system is cheaper than an UAV based one, for example because of the high datarates and necessary downlink of the latter. Research in the area of an UAV based system would be limited to only parts of it, while it seems feasible to develop a prototype vehicle based system.
- the much aclamed merrits of sensor-fusion can be tested. Candidate sensors are discussed in the above presented points 1 to 6.
- it is not covered by the current RSG work programme.

Table 5.2: Provisional time table for a vehicle mounted demonstrator.

	1995	1996	1997	1998	1999	2000	2001
feasibility study	XXXX	XX					
tower masurements	XX	XXXX	XXXX				
demonstrator design			XX	XXXX			
demonstrator construction				XX	XXXX	XX	
demonstrator tests						XXXX	XX

A.N. de Jong
(Group leader)

p.o.

P. Hoogeboom
(Group leader)

Y.H.L. Janssen
(Project leader/Author)

J.S. Groot
(Project leader/Author)

APPENDIX A: ABSTRACTS ON DETECTION WITH RADAR

[A1], [B1, C1, D1, H1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.

- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[A2] "Imaging Of Shallow Subsurface Objects: An Experimental Investigation", T. Ozdemir, S. Roy and R.S. Berkowitz, IEEE Tr.G.&RS., May 1992, 10 pages.

- Experiment with bi-static S-band (3.5 GHz) radar under optimal conditions from 40 cm height. The main drawbacks of this kind of equipment is the disturbance by the air-ground surface (with a possible random roughness) and the (possibly inhomogeneous) subsurface medium.

[A3] "Ground-probing Radar For Plastic And Metallic Mine Detection", R.J. Chignell, journal ?, 1990 ?, 3 pages.

- Description of a portable ground-probing radar system.

[A4] "Further Studies Of A Ground Penetrating Radar For The Detection Of Buried Mines", L. Peters, Ohio State University / US Army Belvoir Research, Development And Engineering Center, July 1990, 16 pages.

- Description of a radar utilising a bi-focal offset reflector antenna. With such an antenna the radar can be used at a greater height than.conventional systems.
- Description of experiments with dummy mines.

[A5], [B2, C2, D3, E2, F1] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.

- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[A6] "'Lantern' Used To Find Gulf Mines", J. Boatman, Jane's Defence Weekly, 29 June 1991, p.1163.

- Underwater mine detection with laser radar.

[A7] "RF Break-through In Mine Detection", ?, 1992, Jane's Defence Weekly, 1/6 page.

- Non-metallic mine detection with a handheld ground-probing radar system.

[A8] "Mine Detection in Dry Soils Using Radar", J.V. Hanson et al., US Army Topography Engineering Center, Fort Belvoir, VA, March 17 1992, 15 pages.

- Description of experiment to detect surface laid and buried metallic/non-metallic mines with an airborne X, C and L band synthetic aperture radar (0.8 * 1.8 m resolution), in very dry soil. Outcome: mines seldom detectable, ground disturbance sometimes.

[A9], [G4] "The Detection of Buried Explosive Objects", J.E. McFee and Y. Das, DRES, Ralston, Canada, Canadian Journal of Remote Sensing, Vol.6, No.2, December 1980, pp.104-121.

- Overview and discussion of close/remote detection techniques/equipment useful for detection of buried mines: magnetometers, electromagnetic induction, electromagnetic radars, acoustic, nuclear detection, trace gas analysis, electromagnetic resonance absorption.

[A10], [G5] "Road Radar Development Project", EBA Canpolar Roadware, July 1992, 8 pages

- Folder of vehicle mounted radar used to profile road pavement structure etc.

[A11], [D7] "Remote Minefield Detection Using Infrared Laser Radar (U)", G.C. Stuart, DRES, Suffield, Canada, November 1988, 125 pages.

- Detailed description of concept laser radar systems carried by RPC's, operating at 10.6 micron wavelength. Discusses system design, simulation results, countermeasures.
- Appendices on noise, speckle, laser, detectors etc.

[A12], [C7, D8] "Multi-sensor Approach to Countermine detection", J.J. Stamboni and J.H. Anapol, Textron Defense Systems, Massachusetts, September 1989, 216 pages.

- Describes application of multi-sensor data fusion to mine detection, in an effort to improve detection/false alarm performance. A survey of mine sensing techniques is summarised. Multi-sensor (passive IR (3-5 micron and 8-12 micron), passive visible, active IR), coincident data is presented from both a ground base platform and an airborne (helicopter) platform. Neural technology is applied to individual mine detection as well as minefield detection. Real time implementation is addressed and demonstrated.
- Contains a 12 page list of references with corresponding abstracts, pictures of mines, sensor descriptions (also of 35 GHz 1 feet resolution radar) etc.

[A13], [B3, C8, D9, E3] "Sensor Fusion III, Proceedings of the congress held 1920 April 1990 in Orlando, Florida", R.C. Harney (ed.), SPIE Washington, 1990, 230 pages.

- Contains 21 papers on algorithms, distributed sensor systems, components for sensor fusion systems and applications. A few papers deal with mine detection.

[A14], [E4] "Sensor fusion techniques", May 1993, 100 pages.

- Papers presented at a 1 day workshop held at TNO-FEL. Various subjects related to fusion techniques: Dempster Shafer theory, Bayesian inference, Kalman filtering, fuzzy logic.

[A15], [B4, D10, H9] "Technieken van en ontwikkelingen in landmijnen en mijnenvelden, een literatuurlijst", A.H.P. Reuser, September 1992, 80 pages.

- Literature list of material available at the library of the Dutch army related to landmines. Contains summaries of 251 magazine articles and reports, mostly in English, sometimes German.

[A16] "UK Notes to NATO RSG on Remote Detection of Minefields", M.I. Dallen, DRA, June 1993, 14 pp.

- NATO restricted.

[A17] "Scatter Mine Detection Radar Experiments", R.M. Berg (Belvoir R&D), March 1984, 21 pp.

- Describes an experiment with an electronically scanned radar to detect, discriminate and locate 155 mm rocket and artillery deployed sub-munitions (e.g., mines). Results are presented in 3D energy vs. time/velocity plots. This report is related to the feasibility study report "Radar Detection of Scatterable Mines" (F.R. Williamson et al., August 1984).

[A18] "Measurement and Analysis of L- and X-band Mine Cross Sections", A.L. Maffett and E.L. Johansen, ERIM, August 1979, 47 pp.

- An echoic chamber and outdoor test range. Measurements on 5 mine types (metal, plastic and wood). Measurements of mine above metal ground planes were not successful.
- Assuming typical background RCS's, it turns out that L-band radar (resolution area 1 m^2) cannot detect individual mines. Detection of minefields is possible in desert areas at low depression angles only.

[A19] "Radar Detection of Scatterable Mines", F.R. Williamson et al., Georgia Tech., August 1984, 223 pp.

- Feasibility study of using a ground-based tracking radar to determine the emplacement locations of scatterable mines (from measurements made during scattering). This extensive report provides target characteristics (155 mm projectiles, MLRS etc.), lab RCS measurements, a live-fire test plan and radar (design) characteristics. However, it does not contain measurement results obtained with a tracking radar. These are included in "Scatter Mine Detection Radar Experiments" (R.M. Berg, March 1984).

[A20] "Minefield Detection Using an Airborne Microwave Radar", I.P.W. Sinclair et al., MPB Technologies Inc., July 1985, 133 pp.

- Includes a literature survey on radar's and radar scattering from terrain, a sub-scale laboratory experiment and a computer simulation.
- The laboratory experiment was carried out at 34 GHz with a vertical looking radar moving at 1 meter height over a sand bed (dry, wet, smooth and rough). Numerous datasets of (scaled down) 2 and 5 cm, buried and unburied "mines" were obtained.
- It was concluded that once the footprint is sufficiently small, detection is possible. Buried mines sometimes featured higer RCS's than unburied ones.

APPENDIX B: ABSTRACTS ON DETECTION WITH MICROWAVE RADIOMETERS

[B1], [A1, C1, D1, H1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.

- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[B2], [A5, C2, D3, E2, F1] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.

- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[B3], [A13, C8, D9, E3] "Sensor Fusion III, Proceedings of the congress held 1920 April 1990 in Orlando, Florida", R.C. Harney (ed.), SPIE Washington, 1990, 230 pages.

- Contains 21 papers on algorithms, distributed sensor systems, components for sensor fusion systems and applications. A few papers deal with mine detection.

[B4], [A15, D10, H9] "Technieken van en ontwikkelingen in landmijnen en mijnenvelden, een literatuurlijst", A.H.P. Reuser, September 1992, 80 pages.

- Literature list of material available at the library of the Dutch army related to landmines. Contains summaries of 251 magazine articles and reports, mostly in English, sometimes German.

[B5] "Microwave Radiometric Studies in Relation to Mine Detection", C.N. Johnson and D.L. Gravitte, US Army R&D laboratories, Fort Belvoir VA, November 1966, 96 pages.

- Laboratory results of measurements with a C-band (5 cm) radiometer indicated that detection of buried mines should be feasible.
- However, field measurements over clay-type soils at Fort Belvoir indicate that such a system is highly unsuitable, due to masking signals even under the most favourable (dry weather) conditions.

[B6] "Feasibility Study of Microwave Detection of Mine Fields", K.J. Keskinen et al., MPB Technologies Inc., March 1989, 95 pp.

- Follow-up of report "Minefield Detection Using an Airborne Microwave Radar" (I.P.W. Sinclair et al., July 1985). Contains an extended literature review, scaled down measurements of backgrounds and model mines.
- The main conclusion is that a down-looking (obligatory due to the specular nature of reflection by horizontal mines) active microwave system should be flown at a low height (<

100 m) and has an unacceptable small swath width of only 2 meters. It is therefore recommended to conduct a study similar to this one with a radiometric (passive) system. The results of this study are reported in "Microwave Radiometry for Minefield Detection" (MPB Technologies Inc., April 1991).

[B7] "Microwave Radiometry for Detection of Metallic Targets", K. Keskinen et al., MPB Technologies Inc. / DRES, In: Proc. of Spec. Meeting on Microw. Radiometry and Rem. Sens. Appl., 1992, 5 pp.

- Series of experiments with roof-mounted 35 and 90 GHz radiometers used to detect uncovered metallic mines.
- Conclusions: detection is possible at both frequencies at beam fill factors (= mine area divided by antenna footprint) down to 0.1, at any incidence angle up to 70 degrees (the target contrast temperature is independent of this angle). The 0.1 lower limit was determined by system noise. If system noise is negligible, natural variations of terrain apparent temperature will set the lower limit. Other targets (plastic mines, rocks, pieces of wood) were not detectable unless the beam fill factor was in the order of unity. This article is a summary of thc report "Microwave Radiometry for Minefield Detection" (MPB Technologies Inc., April 1991).

[B8] "Microwave Radiometry for Minefield Detection", MPB Technologies Inc., April 1991, 62 pp.

- A summary of this report is the article "Microwave Radiometry for Detection of Metallic Targets" (K. Keskinen et al., 1992). An additional observation was that plastic mines could be detected down to beam fill factors 0.2 at 35 GHz. A helicopter-borne version of this system would have a weight of 70 kg and volume of L*W*H= 0.8*0.5*0.4 m^3, respectively, and should be flown at 30 km/hour at a height of 15 m.

[B9] "A Feasibility Study of Radiometry as a Sensor for Military Applications", J. Snieder and W. Keizer (TNO-PML), March 1981, 78 pp.

- Introductory text about microwave radiometry, based on a literature survey. Contains elementary material about practical aspects, like the impact of antenna choice, weather conditions, frequency choice etc. The range equation is used to determine the feasibility of detection of airplanes, persons, ships, tanks etc. Only the detection of airplanes seems impossible. The text ends with a discussion of the (dis)advantages of microwave radiometry.

[B10] "Initial Results in the Development of a Synthetic Aperture Microwave Radiometer", D.M. Le Vine et al., IEEE Tr. on Geosc. and RS., July 1990, 6 pp.

- This L-band (1.4 GHz) airborne synthetic aperture radiometer utilizes an antenna consisting of several sticks, aligned along-track. Along-track resolution is determined by the length of the sticks, while the across-track resolution is determined by the largest distance between two sticks (this is called the synthetic aperture length. For SAR the synthetic aperture is much larger than the physical aperture size). An advantage over a real aperture system is that there is no need to scan the surface in across-track direction to obtain a large swath width. First measurement results demonstrate the valididity of the concept.

[B11] "The Sensitivity of Synthetic Aperture Radiometers for Remote Sensing Applications from Space", D.M. Le Vine, Radio Science, July-August 1990, 13 pp.

- The synthetic aperture antennas discussed consist of a collection of spaced (small) antenna. Synthetic aperture radiometers do not scan cross-track like real aperture systems do. Cross-track image formation is accomplished by processing the data from different antenna pairs with different spacings, instead. The highest (best) spatial resolution is approximately the same as that of an antenna with equal physical dimensions. The radiometric resolution is only marginally worse than that of a real aperture system. A detailed analysis is presented of several synthetic antenna configurations, with the emphasis being on spaceborne remote sensing systems.

APPENDIX C: ABSTRACTS ON DETECTION WITH VISUAL AND NIR SENSORS

[C1], [A1, B1, D1, H1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.

- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[C2], [A5, B2, D3, E2, F1] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.

- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[C3], [D4] "Stand-off Minefield Detection Systems (STAMIDS) Advanced Technology Transition Demonstration (ATTD)", K.G. Hall et al., The Military Engineer, August 1991, 2 pages.

- STAMIDS: sensor in an ULV, data transmitted to ground station, real-time image processing for minefield detection. Description of ATTD phase 1 test September October 1990. Flights over 2530 minefields, two times per day for 3 weeks.
- Sensors: AMIDARS = infrared airborne scanner; REMIDS = optical scanner in helicopter, 3 channels: two active laser polarisation/reflectance, one passive infrared; CMADS = thermal helicopter borne thermal infrared.

[C4], [D5] "Mine/Countermine Research", H.W. West et al., The Military Engineer, August 1985, 3 pages.

- Stand-off detection: high resolution photography, thermal line scanner, multi-frequency optical data. Neutralisation: MICLIC, mine response model. Mine use: wide-area mines etc.

[C5], [D6] "The MIDURA 19821983 Experimental Test Plan", D. Griffith and Y. Morita, ERIM, Michigan, April 1982, 67 pages.

- Detailed test plan (no results) for one year of flights with optical and thermal infrared cameras over areas with buried and surface laid AT minefields.

[C6] "Analysis of Aerial Photography From Array II (1980)", M.B. Walsh, ERIM, Michigan, May 1982, 23 pages.

- Results of AT mine detection experiment with airborne cameras. Contains summary of ARRAY I (conducted July August 1979) results.
- Results: ARRAY I mines better detectable (no magnification necessary) than ARRAY II (magnification necessary).

- Possible causes: different background homogeneity, sun elevation angles/specular reflections, vegetation type. Shadows are the most important detection cue, so direct sunlight is important. Specular reflections are also important.
- Array I: surface laid mines are detectable, buried mines also due to ground disturbances (like furrows).

[C7], [A12, D8] "Multi-sensor Approach to Countermine detection", J.J. Stamboni and J.H. Anapol, Textron Defense Systems, Massachusetts, September 1989, 216 pages.
- Describes application of multi-sensor data fusion to mine detection, in an effort to improve detection/false alarm performance. A survey of mine sensing techniques is summarised. Multi-sensor (passive IR (3-5 micron and 8-12 micron), passive visible, active IR), coincident data is presented from both a ground base platform and an airborne (helicopter) platform. Neural technology is applied to individual mine detection as well as minefield detection. Real time implementation is addressed and demonstrated.
- Contains a 12 page list of references with corresponding abstracts, pictures of mines, sensor descriptions (also of 35 GHz 1 feet resolution radar) etc.

[C8], [A13, B3, D9, E3] "Sensor Fusion III, Proceedings of the congress held 1920 April 1990 in Orlando, Florida", R.C. Harney (ed.), SPIE Washington, 1990, 230 pages.
- Contains 21 papers on algorithms, distributed sensor systems, components for sensor fusion systems and applications. A few papers deal with mine detection.

[C9] "Preliminary Investigations of a High Spectral Resolution Imaging Spectrograph (CASI) for Detection of Surface Scattered Land Mines", R.J. Soofer and J. McFee, ?, 1992 ?, pp. 487-492
- Measurements with a CASI (wavelengths 425-925 nm) operated from a horizontal scanning manlift (cheap compared to aircraft) on natural targets and five Warsaw Pact type mines.
- The mine spectra differ from those of natural targets, suggesting suitability of the CASI for mine detection.

[C10], [D16] "Final Report on a Study of Visible and Infrared Mine Field Detection", Barringer Research Limited, July 1985, 180 pp.
- Presents a general overview based on a literature search, and own work. The latter includes analyses of mine and terrain visible and near infrared (VNIR) spectra, and thermal modelling of buried mines. Main conclusions:
  - in the visible and near infrared bands detection of mine like objects occupying > 20 percent of the pixel area is possible for most terrain types.
  - to discriminate mines from the terrain a minimum of 3 VNIR spectral channels of high spatial resolution is necessary.
  - computer modelling revealed the feasibility of detecting a buried iron layer at depths of up to 20 cm by remote sensing of ground surface temperate anomalies. Vegetation layers greatly reduce this possibility.
- Contains 350 references.

APPENDIX D: ABSTRACTS ON DETECTION WITH MWIR AND LWIR

[D1], [A1, B1, C1, H1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.

- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[D2] "Sensor Fusion Methodology For Remote Detection Of Buried Land Mines", N.D. Grande, Lawrence Livermore National Laboratory, Livermore, April 1990, 21 pages.

- Two channel passive IR system (5 and 10 micron), 60 m height, 0.2 K temperature resolution. Description of (buried) mine detection experiment. It is made plausible that two channel systems have a superior performance compared to one channel systems.

[D3], [A5, B2, C2, E2, F1] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.

- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[D4], [C3] "Stand-off Minefield Detection Systems (STAMIDS) Advanced Technology Transition Demonstration (ATTD)", K.G. Hall et al., The Military Engineer, August 1991, 2 pages.

- STAMIDS: sensor in an ULV, data transmitted to ground station, real-time image processing for minefield detection. Description of ATTD phase 1 test September October 1990. Flights over 2530 minefields, two times per day for 3 weeks.
- Sensors: AMIDARS = infrared airborne scanner; REMIDS = optical scanner in helicopter, 3 channels: two active laser polarisation/reflectance, one passive infrared; CMADS = thermal helicopter borne thermal infrared.

[D5], [C4] "Mine/Countermine Research", H.W. West et al., The Military Engineer, August 1985, 3 pages.

- Stand-off detection: high resolution photography, thermal line scanner, multi-frequency optical data. Neutralisation: MICLIC, mine response model. Mine use: wide-area mines etc.

[D6], [C5] "The MIDURA 19821983 Experimental Test Plan", D. Griffith and Y. Morita, ERIM, Michigan, April 1982, 67 pages.

- Detailed test plan (no results) for one year of flights with optical and thermal infrared cameras over areas with buried and surface laid AT minefields.

[D7], [A11] "Remote Minefield Detection Using Infrared Laser Radar (U)", G.C. Stuart, DRES, Suffield, Canada, November 1988, 125 pages.

- Detailed description of concept laser radar systems carried by RPC's, operating at 10.6 micron wavelength. Discusses system design, simulation results, countermeasures.
- Appendices on noise, speckle, laser, detectors etc.

[D8], [A12, C7] "Multi-sensor Approach to Countermine detection", J.J. Stamboni and J.H. Anapol, Textron Defense Systems, Massachusetts, September 1989, 216 pages.

- Describes application of multi-sensor data fusion to mine detection, in an effort to improve detection/false alarm performance. A survey of mine sensing techniques is summarised. Multi-sensor (passive IR (3-5 micron and 8-12 micron), passive visible, active IR), coincident data is presented from both a ground base platform and an airborne (helicopter) platform. Neural technology is applied to individual mine detection as well as minefield detection. Real time implementation is addressed and demonstrated.
- Contains a 12 page list of references with corresponding abstracts, pictures of mines, sensor descriptions (also of 35 GHz 1 feet resolution radar) etc.

[D9], [A13, B3, C8, E3] "Sensor Fusion III, Proceedings of the congress held 1920 April 1990 in Orlando, Florida", R.C. Harney (ed.), SPIE Washington, 1990, 230 pages.

- Contains 21 papers on algorithms, distributed sensor systems, components for sensor fusion systems and applications. A few papers deal with mine detection.

[D10], [A15, B4, H9] "Technieken van en ontwikkelingen in landmijnen en mijnenvelden, een literatuurlijst", A.H.P. Reuser, September 1992, 80 pages.

- Literature list of material available at the library of the Dutch army related to landmines. Contains summaries of 251 magazine articles and reports, mostly in English, sometimes German.

[D11] "Infrared Reflectance Measurements of Replica Mines and Reference Targets", G.C. Stuart, DRES, Canada, February 1989, 39 pages.

- Presents 10.6 micron reflectance data of replica mines which have been found to be specular (mirror-like) at thermal IR wavelengths, although with a substantial variation in the magnitudes of the returns. This means that such a sensor must be downward-looking and only those mines within a fairly small angular field of view will give significantly large reflected signals.

[D12] "Site Characterisation for Remote Minefield Detection Scanner (REMIDS) System Data Acquisition", K.S. Long and K.G. Hall, USAE Waterways Experiment Station, Vicksburg MS, April 1991, 107 pages.

- Description of study to collect ground truth data from various target arrays in several backgrounds under various environmental conditions to evaluate REMIDS (which uses both passive thermal and active 10.6 micron laser detector arrays). Ground data measured included surface geometry, vegetation parameters, on-site meteorology etc. Mines used: RAAM, M15 and M19. Several flights were performed in both the summer and fall seasons.

[D13], [E2] "Simulation of images by photometric stereo modelling", K.L. Russell, J.E. McFee and M.R. Ito, Optical Engineering, 30(9), September 1991, pp. 1337-1346

- Presents a method to synthesise images resembling those measured by an airborne sensor. Method: create model scene (e.g., from clay with dimensions 10*10 cm) add surface type dependent texture, digitise model under different illumination directions, create depth map with photometric stereo method, compute image from depth map, tables of reflectivity/emissivity data (for each surface type) and flight geometry parameters, add noise > synthetic image.
- Emphasis is on (validation of) the photometric stereo method.
- The photometric stereo method is validated with computer generated images of a bi-variate normal and hemispherical shape. In addition, a real clay-coated hemisphere model is used.
- Finally, the whole algorithm is used to generate a synthetic image of a terrain with landmines in it, mimicing the output of an ideal pushbroom scanner using a 10.6 micron laser.

[D14], [E4] "Computer Vision for Locating Buried Objects", G.A. Clark et al., ?, December 1992 ?, 5 pages

- Experiment with 9-14 inch deep buried surrogate 612 inch diameter mines. The field consisted of sandy-loam covered by grass. Analysis of (ratios of) 5 and 10 micron IR images using Gabor transforms, a neural network etc. results in semiautomatic detection of 6 of the mines.

[D15] "Analysis and Trial of an active longwave infrared imaging system for minefield detection and identification", Jean R. Simard, November 1992, 66 pp.

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[D16], [C10] "Final Report on a Study of Visible and Infrared Mine Field Detection", Barringer Research Limited, July 1985, 180 pp.

- Presents a general overview based on a literature search, and own work. The latter includes analyses of mine and terrain visible and near infrared (VNIR) spectra, and thermal modelling of buried mines. Main conclusions:
  - in the visible and near infrared bands detection of mine like objects occupying > 20 percent of the pixel area is possible for most terrain types.
  - to discriminate mines from the terrain a minimum of 3 VNIR spectral channels of high spatial resolution is necessary.
  - computer modelling revealed the feasibility of detecting a buried iron layer at depths of up to 20 cm by remote sensing of ground surface temperate anomalies. Vegetation layers greatly reduce this possibility.
- Contains 350 references.

[D17], "Introduction to electro-optical imaging and tracking systems", Khalil Seyrafi, S.A. Hovanessian, Artech House, Boston, London, 1993, 260 pp. ISBN 0-89006-672-8

- Presents a general overview on the most resent EO-techniques. Ten capters dealing with respectively 1.Historical development; 2.Optical radiation; 3.Atmospheric transmission; 4.Spectral, Spatial, and Temporal Variations in Infrared Backgrounds; 5.Detection and Discrimination in EO Sensors; 6.EO System Design and Performance Equations; 7. EO Systems Applications; 8.Laser Radar Systems

[D18], "The Infrared & Electro-Optical Systems Handbook, Volume 4: Electro-Optical Systems Design, Analysis, and Testing", Michael C. Dudzik, SPIE Optical Engineering Press, Bellingham, Washington USA, 1993, 352 pp., ISBN 0-8194-1072-1

- System design, analysis, and testing, including adjunct technology and methods such as trackers, mechanical design considerations, and signature modelling. Six chapters containing respectively: 1.Fundamentals of EO Imaging Systems Analysis; 2. EO Imaging System Performance Prediction; 3.Optimechanical Design; 4.Infrared Imaging System Testing; 5. Tracking and Controling Systems; 6. Signature Prediction and Modelling

[D19], "The Infrared & Electro-Optical Systems Handbook, Volume 5: Passive Electro-Optical Systems", Stephen B. Campana, SPIE Optical Engineering Press, Bellingham, Washington USA, 1993, 356 pp., ISBN 0-8194-1072-1

- Contempary infrared passive systems such as FLIR's, IRST's, IR line scanners, and staring array configurations. Four chapters containing respectively: 1.Infrared Line Scanning Systems; 2. Forward-Looking Infrared Systems; 3.Staring-Sensor Systems; 4.Infrared Search and Track Systems

[D20], "The Infrared & Electro-Optical Systems Handbook, Volume 6: Active Electro-Optical Systems", Clifton S. Fox, SPIE Optical Engineering Press, Bellingham, Washington USA, 1993, 312 pp., ISBN 0-8194-1072-1

- Active systems including mostly new material on laser radar, laser range finders, millimeter-wave systems, and fiber optic systems. Four chapters containing respectively: 1.Laser Radar; 2. Laser Rangefinders; 3.Milimeter-Wave Radar; 4.Fiber Optic Systems

APPENDIX E: ABSTRACTS ON MULTISPECTRAL DETECTION

[E1], [A1, B1, C1, D1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.

- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[E2], [A5, B2, C2, D3, F1] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.

- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[E3], [A13, B3, C8, D9] "Sensor Fusion III, Proceedings of the congress held 1920 April 1990 in Orlando, Florida", R.C. Harney (ed.), SPIE Washington, 1990, 230 pages.

- Contains 21 papers on algorithms, distributed sensor systems, components for sensor fusion systems and applications. A few papers deal with mine detection.

[E4], [A14] "Sensor fusion techniques", May 1993, 100 pages.

- Papers presented at a 1 day workshop held at TNO-FEL. Various subjects related to fusion techniques: Dempster Shafer theory, Bayesian inference, Kalman filtering, fuzzy logic.

APPENDIX F: ABSTRACTS ON DATA PROCESSING

[F1], [A5, B2, C2, D3, E2] "Verslag Vergadering AC/243(CET) 9/1210/12 Brussel" (minutes of the meeting in Dutch, sheets etc. in English), T. van Koersel, December 1991.

- A set of summaries/copied sheets of material presented at a AC/243(CET) meeting. The Canadian contribution summarises the DRES research on ultraviolet, radar, radiometer, optical and infrared sensors. Another research area is image simulation and image processing.

[F2], [D13] "Simulation of images by photometric stereo modelling", K.L. Russell, J.E. McFee and M.R. Ito, Optical Engineering, 30(9), September 1991, pp. 1337-1346

- Presents a method to synthesise images resembling those measured by an airborne sensor. Method: create model scene (e.g., from clay with dimensions 10*10 cm) add surface type dependent texture, digitise model under different illumination directions, create depth map with photometric stereo method, compute image from depth map, tables of reflectivity/emissivity data (for each surface type) and flight geometry parameters, add noise > synthetic image.
- Emphasis is on (validation of) the photometric stereo method.
- The photometric stereo method is validated with computer generated images of a bi-variate normal and hemispherical shape. In addition, a real clay-coated hemisphere model is used.
- Finally, the whole algorithm is used to generate a synthetic image of a terrain with landmines in it, mimicing the output of an ideal pushbroom scanner using a 10.6 micron laser.

[F3] "A classifier for feature vectors whose prototypes are a function of multiple continuous parameters", J.E. McFee and Y. Das, IEEE Tr. on Pattern Analysis and Machine Intelligence, 10(4), July 1988, pp. 599-606.

- Describes a classification algorithm suited to the problem of assigning classes and in addition (a) continuous parameter(s), based on measured feature vectors. The algorithm is tested on computer generated magnetic dipole moments (sometimes including noise) which are used as feature vectors to classify a set of 6 homogeneous different sized ferrous spheroids (models for artillery shells) and their orientation (3 continuous parameters) placed in the Earth's magnetic field. The results are generally better than those of the nearest mean vector, Fisherpairwise, 1NN and Parzen classifiers.

[F4], [D14] "Computer Vision for Locating Buried Objects", G.A. Clark et al., ?, December 1992 ?, 5 pages

- Experiment with 9-14 inch deep buried surrogate 612 inch diameter mines. The field consisted of sandy-loam covered by grass. Analysis of (ratios of) 5 and 10 micron IR images using Gabor transforms, a neural network etc. results in semiautomatic detection of 6 of the mines.

[F5] "Techniques for the Detection of Land Mine Fields, Using Imaging Sensors" (draft), C.M. Birkemark and P.G. Jensen, Danish Defence Research Establishment, December 1993, 10 pp.

- Describes some data processing techniques applicable to mine (field) detection. Tow levels: isolated spot (mine) detection, followed by aggregation into lines or complex shapes. There are no tests on real data included.

[F6] "Detection of Surface-laid Minefields Using a Hierarchical Image Processing Algorithm", J.E. McFee et al., SPIE Appl. of Dig. Im. Proc., 1991, 11 pp.

- Outline of algorithm: raw data > pre-processing (correct image imperfections) > target cueing (reject regions without mines) > target shape analysis (recognise mine shaped objects) > target spatial analysis (recognise mine fields) > user.
- Generally, the data rate decreases while the algorithm complexity increases along this chain.
- The algorithm was implemented and tested up to and including the "target shape analysis" step on synthetic *10600* nm images. It detected reliably and consistently the mines present, although not in real time. Real time implementation is feasible.

[F7] "Analysis of Minefield Images Using a Transputer Network", J.E. McFee et al., Transp. Res. & Appl., 1993, 17 pp.

- Detailed description of transputer implementation of several stages of a multi-stage minefield detection algorithm.
- Outline of algorithm: raw data > pre-processing (correct image imperfections) > target cueing (reject regions without mines) > target shape analysis (recognise mine shaped objects) > target spatial analysis (recognise mine fields) > user.
- The two stages covered are target cueing and target shape analysis. Estimated costs for the complete network are 100 kUS$.

[F8] "Introduction to Mathematical Morphology", J. Serra, Computer Vision, Graphics, and Image Processing, 1986, pp. 283-305

- Average complex mathematically oriented introduction to the subject of binary mathematical morphology. Describes (almost) all morphological operations. Gives a few examples.

[F9] "Application of Morphological Transformations to the Analysis of Tw-Dimensional Eletrophoretic Gels of Biological Materials", M.M. Skolnick, Computer Vision, Graphics, and Image Processing, 1986, pp.306-332

- Discusses the example of the title in a concise clear way, with a minimal mathematical explanation. Morphological fiters are user to get rid of background, streak and random noise contamination, a.o..

[F10] "Grayscale Morphology", S.R. Sternberg, Computer Vision, Graphics, and Image Processing, 1986, pp.333-355

- Extension of binary morphology to greyscale morphology. Includes a noise removal example. Ends with a discussion of greyscale homotopy.

[F11] "Automatic Screening of Cytological Specimens", F. Meyer, Computer Vision, Graphics, and Image Processing, 1986, pp. 356-369

- Application of binary and greyscale morphology to the automatic screening of cytological specimens. Multi stage algorithm, using several different morphological operators.

[F12] "Morphological Structuring Element Decomposition", X. Zhuang and R.M. Haralick, Computer Vision, Graphics, and Image Processing, 1986, pp. 370-382

- Mathematical treatment of decomposition. Decomposition is needed to implement morphological transformations in a pipelined machine.

[F13] "Automated Basin Delineation from Digital Elevation Models using Mathematical Morphology", P.J. Soille and M. Ansoult, Signal Processing, 1990, pp. 171-182

- Automatic extraction of basin boundaries from a DEM, using morphological operations. The result compares well with ground survey results.

[F14] "Watersheds in Digital Spaces: An Efficient Algorithm Based on Immersion Simulations", L. Vicent and P. Soille

- Presents a fast (computation time proportional to the number of pixels) algorithm to compute watersheds in digital grayscale images. Applications to image segmentation and a DEM are included.

[F15] "Morphological Algorithms", L. Vincent, in "Mathematical Morphology in Image Processing", editor E. Dougherty, September 1992

- Presents pseudo code for the efficient implementation of several morphological operations: distance function, granulometry function, geodesic reconstruction, skeleton, watershed. Includes example applications.

[F16] "Mathematical Morphology: a Geometrical Approach in Image Processing", H.J.A.M. Heijmans, Nieuwe Archief voor Wiskunde, November 1992

- Highly mathematical treatment of several morphological operations. Contains nevertheless some clear examples.

[F17] "An Overview of Morphological Filtering", J. Serra and L. Vincent, Circuits Systems Signal Processing, January 1992, pp. 47-108

- Tutorial overview of mnorphological filtering, including the mathematical foundation. Contains a clear description of the application to the segmentation of grayscale images (pp. 86-89).

[F18] "Morphological Tranformations of Binary Images with Arbitrary Structuring Elements", L. Vincent, Signal Processing, January 1991, pp. 3-23

- Describes a fast algorithm for morphological transformations with arbitrary structuring elements. Contains pseudo code.

[F19] "Morphological Systems for Multidimensional Signal Processing", P. Maragos and R. Schafer, Proc. of the IEEE, April 1990, pp. 690-710

- Review paper. Includes sections on rank-order noise filtering (which is a generalization of median filtering), multiscale openings/closins, edge/line enhancement, detection, skeleton transformations and fractals.

[F20] "Image Analysis Using Mathematical Morphology", R.M. Haralick, S.R. Sternberg and X. Zhuang, IEEE Tr. on PAMI, July 1987, pp. 532-550

- Very readable introduction on the subject. Gently introduces the binary dilation, erosion, opening and closing operations. This is extended to their greyscale counterparts.

[F21] "Analysis of Remotely Sensed Imagery Using Digital Morphology", F.W. Rohde, NASA STAR Technical Report Issue 21, 1988, 10 pages

- Very simple introduction to binary morphology. Gives examples of dilation, erosion and the hit-or-miss transforms. Only scratches the surface of the application to remote sensing.

[F22] "Three Dimensional Morphology for Target Detection", T.J. Patterson, SPIE Vol. 1471, 1991, pp. 358-368

- Gives first a clear, pictorial introduction into three-dimensional (grey-scale) morphology. Compares a target detection system including morphological filters to one without, with SAR data as input. The morphological (non-morphological) detector provides a 93 % (70 %) detection probability at a false alarm rate of 0.6 (200) per unit area.

[F23] "Some Applications of Mathematical Morphology to Range Imagery", J.G. Verly and T.R. Esselman, International Electronic Imaging Exposition and Conference, 1988, pp. 280-285

- Short (2 text pages), heavily illustrated article on the application to LIDAR imagery and synthetic imagery. Applications are noise removal, appendage extraction and corner extraction.

[F24] "Tutorial on Advances in Morphological Image Processing and Analysis", P. Maragos, Optical Engineering, July 1987, pp. 623-632

- A review of some recent advances in the theory and applications of morphological image analysis. Applications touched are noise suppression, edge detection, region filling, skeletonization, smoothing etc. Contains 3 clear tables summarizing the definition of set-processing, function-processing and function/set-processing filters.

[F25] "Advances in Image Analysis", Y. Mahdavieh, R.C. Gonzalez, SPIE Optical Engineering Press, Bellingham, Washington , USA, 1992, 557 pp., ISBN 0-8194-1047-0

- A review of recent advances in image analysis. The main areas covered are image enhancement, edge detection, image segmentation, feature extraction, morphology, motion analysis and industrila applications.

APPENDIX G: ABSTRACTS ON CLOSE-IN DETECTION

[G1] "Advances In The Detection Of Landmines", J.E. McFee en Y. Das, DRES, Suffield, Canada, October 3 1991, 83 pages.

- Close-in detection: methods to detect explosives (microwave resonant absorption, nuclear radiation, trace gas detection, biochemical detection); methods to detect the casing (magneto-static, E.M. induction, impedance topography, E.M. radar, acoustical, optical). Remote detection not covered.

[G2] "Close-In Mine Detection", W. Comeyne, US Army Belvoir RD & E. Center, 1991 ?, 17 pages.

- Sheets about close-in mine detection.

[G3], [H3] "Land Mines and Countermeasures; the Continuing Duel", T.J. O'Malley, Armada International 6/1990, 5 pages.

- Describes several mine types and clearance methods: metal detector, Giant Viper, ploughs/rollers/flails, Vehicle Magnetic Signature Duplicator (neutralises magnetic influence mines) etc.

[G4], [A9] "The Detection of Buried Explosive Objects", J.E. McFee and Y. Das, DRES, Ralston, Canada, Canadian Journal of Remote Sensing, Vol.6, No.2, December 1980, pp.104-121.

- Overview and discussion of close/remote detection techniques/equipment useful for detection of buried mines: magnetometers, electromagnetic induction, electromagnetic radars, acoustic, nuclear detection, trace gas analysis, electromagnetic resonance absorption.

[G5], [A10] "Road Radar Development Project", EBA Canpolar Roadware, July 1992, 8 pages

- Folder of vehicle mounted radar used to profile road pavement structure etc.

[G6] "Vapour measurements above buried land mines. Model experiments using methyl 14C TNT", M.S. Nieuwenhuizen et al., J. Energ. Mat. 8, 1990, pp.256-307.

- On close-in detection of mines by detection of vapour of explosives. Measurement results.

[G7] "Detection of clandestine explosives", M.S. Nieuwenhuizen, TNO-PML, The Netherlands, 31 pages.

- Describes several methods for close-in detection of explosives (X-Ray detection, neutron detection, RF resonance, vapour detection, mass spectrometry etc.). Contains 12 page reference list.

APPENDIX H: ABSTRACTS ON OTHER DETECTION TOPICS

[H1], [A1, B1, C1, D1] "German Research And Technology Activities In The Fields Of Mine Detection And Mine Clearing", MOD GE, Bonn, May 14 1992, 14 pages.
- Overview of mine detection methods: infrared photography, acoustic, harmonic radar, holographic interferometry, geophysical radar (0.81 GHz), microwaves (1 GHz).
- Minefield detection: imaging system detects mine (patterns) or remaining mine layer tracks; image processing.
- Mine clearing: explosive methods, mechanical methods (water/gas jet, laser, bulldozer).

[H2] "Activity Fields Of The Electronic Equipment Service", DGA, June 1992, 16 pages.
- Sheets about remote mine detection, partially in French.

[H3], [G3] "Land Mines and Countermeasures; the Continuing Duel", T.J. O'Malley, Armada International 6/1990, 5 pages.
- Describes several mine types and clearance methods: metal detector, Giant Viper, ploughs/rollers/flails, Vehicle Magnetic Signature Duplicator (neutralises magnetic influence mines) etc.

[H4] "Land Mine Warfare Recent Lessons And Future Trends", Maj. J.R. Wyatt, 1989, 6 pages.
- Summary of mine laying and clearance techniques.

[H5] "Land Mines Cheap And Effective Area denial", M. Hewish, International Defence Review, 8/1986, pp. 1085-01091.
- Article with details about AT/AP mine types and deployment methods.

[H6] "UDT '91, a diversity of technology", D. Foxwell, International Defence Review 6/1991, p.649.
- Underwater mine detection with sonar.

[H7] "Mined Where You Go", W. Fowler, Defence, September 1990, 4 pages.
- Description of all kinds of AT/AP mines with different fuses and working mechanisms.

[H8] "Belvoir Developing Countermine Technologies", Gayle Peterson, Army RD & Acquisition Bulletin, September, October 19888, pp. 20-21
- Mostly about mine neutralisation (MICLIC etc.)

[H9], [A15, B4, D10] "Technieken van en ontwikkelingen in landmijnen en mijnenvelden, een literatuurlijst", A.H.P. Reuser, September 1992, 80 pages.
- Literature list of material available at the library of the Dutch army related to landmines. Contains summaries of 251 magazine articles and reports, mostly in English, sometimes German.

[H10] "Cambodja bezaaid met mijnen" (in Dutch), H. van Zwet, Defensiekrant page 5, February 1993, 1 page.

- About UN mission which aims at learning Cambodians how to clear local minefields.

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10. TITLE AND SUBTITLE

REMOTE LAND MINE(FIELD) DETECTION
an overview of techniques

11. AUTHOR(S)

J.S. Groot
Y.H.L Janssen

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Physics and Electronics Laboratory, P.O. Box 96864, 2509 JG The Hague, The Netherlands
Oude Waalsdorperweg 63, The Hague, The Netherlands

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The classification designation Ongerubriceerd is equivalent to Unclassified, Stg. Confidentieel is equivalent to Confidential and Stg. Geheim is equivalent to Secret.

15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

A near real time land mine(field) detection system is essential for military commanders to enable them to circumvent the mines, or to allocate/employ mine neutralisation/breaching assist to clear a safe route through a minefield.
Basic principles and strengths and weaknesses of such a system with visual, near infrared, midwave infrared, longwave infrared, microwave radiometric and radar sensors are presented.
Recommendations for a vehicle mounted multi-sensor demonstrator system are given since the "Genie" expressed its interest in such a system, it is cheaper than an aircraft mounted system and because sensor fusion can be tested and applied relatively easy on such a system.
Promising techniques for a vehicle mounted detection system are:
1. passive and active infrared imaging,
2. microwave radiometry,
3. passive and active visual and near infrared wavelength discrimination,
4. radar ground and vegetation penetration.
Proposed steps in the development of a vehicle mounted mine detection demonstration system are a feasibility study, tower measurements and design, construction and testing of the demonstrator.

16. DESCRIPTORS	IDENTIFIERS
Mine detection	Infrared mine detection
Microwave mine detection	Remote detection
	Close in detection

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Electronic References

Internet Locations

CAUTION: The following URLs are current as of the date of publication, however URLs change.

MINERATS: Anti-personnel mine clearance robots

URL: *http://www.fourmilab.ch/minerats/*

This location describes the Minerats project and supplies links to many other related locations. The Geneva UN Mine Clearance Meeting Report and pictures of frequently-encountered antipersonnel mines courtesy of the International Committee of the Red Cross, are included. The Geneva UN Mine Clearance Meeting Report has an excellent bibliography at the end.

ICRC: International Committee of the Red Cross

URL: *http://www.icrc.ch/icrcnews/2276.htm*

The ICRC is very concerned about the tragic and indiscriminate effects of anti-personnel mines which kill and maim thousands of civilians each year. This location contains basic facts and information about land mines, a bibliography, and press releases and news items on anti-personnel weapons. This is an excellent location for information.

JAYCOR: Standoff Mine Detection Radar System

URL: *http://www.jaycor.com/Mine/Mine.html*

Describes the JAYCOR standoff mine detection system. This system is the only known system that can detect and identify mine types at a substantial range (~50 feet) with a false detection rate (<1%). It can detect both surface and buried mines.

GDE Systems Integrated Mine Detection

URL: *http://www.gdesystems.com/ATS/SlipSheets/mines.html*

Describes GDE Ground Penetrating Radar (GPR) mine detection and technology.

Transcript: DoD News Briefing: Thursday, December 7, 1995 - 2 p.m.

http://www.dtic.mil/defenselink/news/Dec95/t120895_teste120.html

DoD News Briefing. Lt. Gen. Howell Estes, III, USAF, JCS/J3

Camber Corporation: Washington Technology Center

URL: *http://www.camberva.com/WashTechCenter/target.html*

Demonstration of an automatic target recognition algorithm simulation and evaluation tested for mine detection algorithms. This is a real time mine detection system developed for humanitarian demining in Bosnia.

Mennonite Central Committee

URL: http//www.mennonitecc.ca/mcc/programs/peace/land-mines.html

Mennonite Central Committee offers numerous reports, proceedings, and meetings on the topic of mine clearance and land mine detection.

GAO Reports

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Document: [NSIAD-96-14] Peace Operations: Effect of Training, Equipment, and Other Factors in Unit Capability
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✦ Included in *The DTIC Review*, March 1996

Additional References

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ADA 300930

NAVAL POSTGRADUATE SCHOOL MONTEREY CA
DEPT OF MECHANICAL ENGINEERING

(U) Sensors for the Detection of Land-Based Munitions✦

SEP 95 29P
PERSONAL AUTHORS: Healey, A. J.; Webber, William T.
REPORT NO: NPS-ME-S5-003

UNCLASSIFIED REPORT

ABSTRACT: (U) This report provides a summary of current land-based munition detection sensor development. Sensors are categorized based upon the principle of their operation: electromagnetic, conductive, mechanical optical, acoustic, and chemical. Each category is subdivided into particular operational sensor types. Theory of operation for each particular sensor type is provided, as well as a discussion of advantages and disadvantages of each. A discussion of sensor performance is included. The final section of the report is a survey of commercially available munition detection sensors along with comments concerning their performance.

DESCRIPTORS: (U) *MINE DETECTION, *MINE CLEARANCE, *LAND MINES, *EXPLOSIVES DETECTION, *UNEXPLODED AMMUNITION, INFRARED DETECTION, DEVELOPING NATIONS, ELECTROMAGNETIC FIELDS, OPTICAL DETECTION, ROBOTS, ACOUSTIC DETECTION, RADAR, BACKSCATTERING, X RAYS, ELECTROMAGNETIC RADIATION, AMMUNITION, LAND USE, ELECTROMAGNETISM, MAGNETOSTRICTION, CHEMICAL DETECTION, MAGNETIC DETECTION.

ADA 300773

GENERAL ACCOUNTING OFFICE WASHINGTON DC
NATIONAL SECURITY AND INTERNATIONAL
AFFAIRS DIVISION

(U) Unexploded Ordnance: A Coordinated Approach to Detection and Clearance is Needed✦

SEP 95 30P
REPORT NO: GAO/NSIAD-95-197

UNCLASSIFIED REPORT

SUPPLEMENTARY NOTE: Report to Committee on National Security, U S. House of Representatives

ABSTRACT (U) Over the past 2 years, several accounts of the casualties caused by antipersonnel land mines have brought to light the threat such munitions pose years after hostilities cease. The deaths and injuries attributed to these mines each year have been estimated to total about 30,000. Many of the victims are civilians including children. While the contamination of land caused by land mines and other forms of unexploded ordnance (UXO) may appear to be primarily a Third World issue, closer examination suggests that the problem is shared by developed nations as well. As you requested, we assessed the extent to which ongoing or foreseeable technology efforts offer solutions to worldwide land mine and other UXO problems.

DESCRIPTORS: (U) *MINE DETECTION, *MINE CLEARANCE, ANTIPERSONNEL MINES, *EXPLOSIVE ORDNANCE DISPOSAL, UNEXPLODED AMMUNITION, INFRARED DETECTION, MICROWAVES, RADAR, BACKSCATTERING, LASER BEAMS, SAFETY, CASUALTIES, WOUNDS AND INJURIES, LAND MINES.

✦ Included in *The DTIC Review*, March 1996

ADA 294394

TEXAS UNIV AT AUSTIN APPLIED RESEARCH LABS

(U) Physics of Buried Mine Detection and Classification

MAY 95 15p
PERSONAL AUTHORS: Chotiros, Nicholas P.; Muir, Thomas G.; Smith, D. E.
CONTRACT NO:N00014-94-I-0485

UNCLASSIFIED REPORT

SUPPLEMENTARY NOTE: Original contains color plates: All DTIC/NTIS reproductions will be in black white.

ABSTRACT: (U) The physics of buried mine detection in offshore sediments and in the surf zone was investigated. Optical techniques are useless because they cannot penetrate sediments while magnetic techniques are of low value because of low resolution, short range, and the introduction of non-magnetic mines. For buried mine detection in the off-shore sediment acoustic penetration at shallow grazing angles was explored. An experiment was conducted jointly with SACLANTCEN to measure sound propagation into a sediment in the 500 HZ to 2 kHz band and a theoretical fast field model was developed to model the penetration. In the surf zone, where bubble clouds are expected to render acoustic methods unreliable, seismic sonar methods were explored as a means to echo range off buried targets. Tests with controlled pulses revealed that the far-field response was dominated by two interface waves. The results have been very encouraging.

DESCRIPTORS: (U) MINE DETECTION, *PHYSICS, *MODEL TESTS *ACOUSTIC MEASUREMENT, *BURIED OBJECTS, *SEDIMENTS, *OFFSHORE, ANGLES, CLOUDS, MEASUREMENT, METHODOLOGY, OPTICS, MAGNETIC FIELDS, MAGNETIC PROPERTIES, MODELS, *INTERFACES, ACOUSTIC WAVES, THEORY, FAR FIELD, TARGETS PENETRATION, PULSES, RESPONSE, BUBBLES, SOUND TRANSMISSION, SHORT RANGE (DISTANCE), SONAR, LAND MINES, LOW RESOLUTION, SEISMOLOGY, ECHO RANGING, SURF MINES (ORDNANCE), SHALLOW DEPTH, GRAZING.

IDENTIFIERS: (U) SHALLOW GRAZING ANGLES

ADA 295074

NAVAL EXPLOSIVE ORDNANCE DISPOSAL TECHNOLOGY CENTER INDIAN HEAD MD

(U) Evaluation of Individual Demonstrator Performance at the Unexploded Ordnance Advanced Technology Demonstration Program at Jefferson Proving Ground (Phase1)

MAR 95 194P

UNCLASSIFIED REPORT

SUPPLEMENTARY NOTE: Prepared in collaboration with Institute for Defense Analyses, Alexandria, VA .

ABSTRACT: (U) The data contained in this report is a supplement to report SFIM-AEC-ET-CR-94120, "Unexploded Ordnance Advanced Technology Demonstration Program at Jefferson Proving Ground (Phase I)". This report provides a further analysis of the individual demonstrators and the performance of their systems when used to detect, identify and/or remedy buried unexploded ordnance under realistic, controlled conditions.

DESCRIPTORS: (U) *UNEXPLODED AMMUNITION, CONTROL, DETECTION, DEMONSTRATIONS, IDENTIFICATION, BURIED OBJECTS.

IDENTIFIERS: (U) REMEDIATION

ADA 295153

NAVAL EXPLOSIVE ORDNANCE DISPOSAL TECHNOLOGY CENTER INDIAN HEAD MD

(U) Ground Penetrating Radar for Ordnance Contaminated Site Restoration

MAR 95 348P
REPORT NO: N00174-93-C-0047

UNCLASSIFIED REPORT

ABSTRACT: (U) The main purpose of this document is to apply ground penetrating radar (GPR) technology to the problem of locating and identifying buried ordnance at military sites. The emphasis of the research applied GPR technology to an airborne system that will allow very large parcels of land to be processed. This contract represents one portion of an overall U.S Government program to clear former and present military ordnance ranges of all unexploded ordnance and other buried devices that pose a threat to the public.

DESCRIPTORS: (U) *RADAR *CONTAMINANTS, *EARTH PENETRATING DEVICES, *UNEXPLODED AMMUNITION, MILITARY FACILITIES, AIRBORNE, SITES, BURIED OBJECTS, ORDNANCE, RANGES (FACILITIES).

ADA 292907

MOORE SCHOOL OF ELECTRICAL ENGINEERING PHILADELPHIA PA
VALLEY FORGE RESEARCH CENTER

(U) Research in Ground-to-Air Microwave Imaging

MAR 95 29P
PERSONAL AUTHORS: Steinberg, Bernard D.; Carlson, Donald
REPORT N0: UP-VFRC-11-95
CONTRACT NO:DAAL03-89-K-0066

UNCLASSIFIED REPORT

ABSTRACT: (U) Many potential applications exist for high resolution radar such as direction finding, high accuracy tracing, target counting, and high resolution radar imaging. All of these applications require the use of large, thinned, random or periodic antenna arrays. Many uncertainties exist in such large antenna systems. For example, exact element positions are generally not known because of surveying problems or flexing of the large antenna structure. Adaptive beanforming (ABF) is the solution to the unusual design that achieves these objectives. It deduces the errors in the locations of the receivers that are distributed around the airport or on the air frame and automatically compensates for them in the image processing. This year's work concentrated on three tasks. The first was to develop a generalized ABF theory for the class of spatial correlation algorithms. The second was to extend the resolution of a microwave leading radar to 15 cm, and the third was to study enhanced target detection sensitivity and target recognition.

DESCRIPTORS: (U) *IMAGE PROCESSING, *RADAR IMAGES, *MICROWAVE OPTICS, ALGORITHMS, NEURAL NETS, TARGET RECOGNITION, MINE DETECTION, RADAR TRACKING, DIRECTION FINDING, HIGH RESOLUTION, BEAM FORMING, GROUND VEHICLES, ANTENNA ARRAYS, X BAND, KU BAND, S BAND.

ADA 295760

PRC INC INDIAN HEAD MD

(U) System/Design Trade Study Report for the Navigation of the Airborne, Ground Vehicular and Man-Portable Platforms in Support of the Buried Ordnance Detection, Identification, and Remediation Technology✦

MAR 95 79P
CONTRACT NO:NOO6OO-88-D-3717

UNCLASSIFIED REPORT

ABSTRACT: (U) This document contains a System Design Trade Study on the optimum navigation systems for airborne, ground-vehicle and man-portable Unexploded Ordnance detection platforms. This study will be used by Unexploded Ordnance Advanced Technology Demonstration decision-makers to make informed technical and programmatic decisions concerning the use of new navigation and location technologies in the detection, identification and remediation of Unexploded Ordnance.

DESCRIPTORS: (U) *NAVIGATION *GROUND VEHICLES *MANPORTABLE EQUIPMENT, *UNEXPLODED AMMUNITION, GROUND LEVEL, OPTIMIZATION, COMMERCE, DETECTION, PLATFORMS, BURIED OBJECTS, ORDNANCE.

ADA 289874

ARMY RESEARCH LAB ADELPHI MD

(U) Research Support for the Depth and Simultaneous Attack Battle Lab

JAN 95 68P
PERSONAL AUTHORS: Kovel, Steven; Brand, John
REPORT NO: ARL-SR-23

UNCLASSIFIED REPORT

ABSTRACT: (U) We performed an assessment of the 6.1/6.2 sensor technology programs that support four of the operational capability requirements (OCRs) related to real-time targeting, formulated by the Depth and Simultaneous Attack Battle Lab. The assessment focused on (1) how the research programs support the OCRs and (2) which research programs are required to support each OCR. Four programs were found to have the greatest potential for supporting the OCRs: Automatic Target Detection Recognition-Identification, Radar Sensor and Signature Research, Snort Fines Sensor System, and Ultra-Wideband Foliage-Penetrating Synthetic Aperture Radar. These programs were selected based on the information generated by these sensor technologies. In addition, we identified the need for realistic war game simulations that incorporate these sensor program concepts, in order to quantitatively evaluate the concepts. In assessing the support required by the OCRs, we found that automatic target recognition was least mature link, and we recommend that the greatest effort be in developing this technology. Finally, we found that the battlefield damage assessment OCR requires a clearer definition before a technology assessment can be performed.

DESCRIPTORS: (U) *TARGET RECOGNITION, *TARGETING, *RADAR SIGNATURES, SIMULATION, MILITARY REQUIREMENTS, REAL TIME, BATTLEFIELDS, DAMAGE ASSESSMENT, ATTACK, MINE DETECTION SYNTHETIC APERTURE RADAR, PENETRATION, RADAR RECEIVERS, WAR GAMES, SYNCHRONISM, RESEARCH MANAGEMENT, BATTLES, LAND MINES, FOLIAGE.

✦ Included in *The DTIC Review*, March 1996

ADA 289786

TEXAS UNIV AT AUSTIN APPLIED RESEARCH LABS

(U) Semi-Annual Performance Report on Physics of Buried Mine Detection and Classification

JAN 95 8P
CONTRACT NO:N00014-94-1-0485

UNCLASSIFIED REPORT

ABSTRACT (U) A better understanding of the science and engineering of buried mine detection in (1) offshore and (2) surf zone sediments, leading to safe, standoff detection technologies. This project is part of a leveraged investment program for ONR and APPA offices, which involves SPECWAR and USMC interests, to pursue major research thrusts already begun by the authors, that will lead the way to systems development. The work is further leveraged by the cooperation of the SACLANT Undersea Research Center (SACLANTCEN) which will provide cooperating seafloor scientists, research tools and research vessels in a joint effort to research the basic physics of the governing processes.

DESCRIPTORS (U) *MINE DETECTION, *SEDIMENTS, *UNDERWATER MINES, DETECTION, STANDOFF, PHYSICS HYDROPHONES, BURIED OBJECTS, OCEAN BOTTOM, SURF, SCIENTISTS, RESEARCH SHIPS

IDENTIFIERS (U) *BURIED MINE DETECTION

ADA 289856

DEFENCE RESEARCH ESTABLISHMENT SUFFIELD RALSTON (ALBERTA)

(U) Experimental Evaluation of the Apparent Temperature Contrast Created by Buried Mines as Seen by an IR Imager✦

NOV 94 35P
PERSONAL AUTHORS: Simard, Jean-Robert
REPORT NO: DRES-SR-607

UNCLASSIFIED REPORT

SUPPLEMENTARY NOTE: Abstract in French and English

ABSTRACT (U) The detection of buried mines is a problem of prime interest internationally. One potential method to succeed in this task is to use passive IR imaging to form thermal images of the soil surface. Even though this technique has been intensively investigated for the last 15 years, only few publicly reported studies show quantitative measures of the apparent temperature contrast at the soil surface above buried mines. This document aims to improve this situation. Apparent temperature contrasts are measured for different mine soil combinations over 24 hour periods with a camera sensitive to long wave infrared (8-12 Micrometer). The effect of the variation of burial depth is investigated and special attention is taken to differentiate the thermal effects associated with the soil disturbance from the mine itself. A maximum average of 2 degrees C in apparent thermal contrast disappears when the burial depth exceeds 8 cm for the case where the thermal disturbance is related to the buried mine only. A 50% increase (-3 degrees C) is observed when the thermal effect of the soil disturbance is present. Furthermore, this last apparent thermal contrast shows little dependency with the burial depth. These results are promising for the detection of mines buried in compacted soil. However, serious reservations about an acceptable false alarm rate and the duration of the thermal effected created by the soil disturbance are expressed.

DESCRIPTORS (U) *INFRARED IMAGES, TEST AND EVALUATION, THERMAL PROPERTIES, CONTRAST, TEMPERATURE, MINE DETECTION, CANADA, RATES, FALSE ALARMS, DEPTH, VARIATIONS, SURFACES, SOILS, BURIED OBJECTS, INFRARED RADIATION, LONG WAVELENGTHS, LAND MINES, THERMAL IMAGES, MINES (ORDNANCE).

✦ Included in *The DTIC Review*, March 1996

ADA 288635

FYSISCH EN ELEKTRONISCH LAB TNO THE HAGUE (NETHERLANDS)

(U) REMOTE LAND MINE (FIELD) DETECTION. An Overview of Techniques (DETECTIE VAN LANDMIJNEN EN MIDNENVELDEN OP AFSTAND. Een Overzicht van de technieken)✦

SEP 94 52P
PERSONAL AUTHORS: Groot, J S.; Janssen, Y. H.
REPORT NO: FEL-94-A205

UNCLASSIFIED REPORT

SUPPLEMENTARY NOTE: Text in English; Abstract in English and Dutch.

ABSTRACT (U) A near real time land mine (field) detection system is essential for military commanders to enable them to circumvent the mines, or to allocate/employ mine neutralization/breaching assist to clear a safe route through a mine field. Basic principles and strengths and weaknesses of such a system with visual, near infrared, midwave infrared, longwave infrared, microwave radiometric and radar sensors are presented. Recommendations for a vehicle mounted multi-sensor demonstrator system are given since the Genie expressed its interest in such a system, it is cheaper than an aircraft mounted system and because sensor fusion can be tested and applied relatively easy on such a system. Promising techniques for a vehicle mounted detection system are: (1) passive and active infrared imaging, (2) microwave radiometry, (3) passive and active visual and near infrared wavelength discrimination, (4) radar ground and vegetation penetration. Proposed steps in the development of a vehicle mounted mine detection demonstration system are a feasibility study, tower measurements and design, construction and testing of the demonstrator.

DESCRIPTORS (U) *MINE DETECTION, *LAND MINES, *MINE DETECTORS, GROUND LEVEL, NETHERLANDS, MINE FIELDS, PASSIVE SYSTEMS, MICROWAVE EQUIPMENT, RADAR, PENETRATION FEASIBILITY STUDIES, INFRARED IMAGES, DATA FUSION RADIOMETERS, INFRARED RADIATION, LONG WAVELENGTHS , VEGETATION, MULTISENSORS, REMOTE DETECTION, NEAR INFRARED RADIATION, RADIOMETRY.

ADA 281162

INSTITUTE FOR DEFENSE ANALYSES
ALEXANDRIA VA

(U) SIMNET-Based Tests of Antihelicopter Mines

JAN 94 58P
PERSONAL AUTHORS: Schwartz, Richard E.; DeRiggi, Dennis F.
REPORT NO: IDA-P-2913
CONTRACT NO:MDA903-89-C-0003

UNCLASSIFIED REPORT

ABSTRACT: (U) This report describes a series of SIMNET Semi-automated Forces armor engagements in which antihelicopter mines are deployed. The impact of two types of antihelicopter mines on armor exchange ratios and other combat measures is presented. Learning effects are analyzed for both types of mines. Antihelicopter mines can have a significant effect on small unit engagements when used in conjunction with an effective air defense system. Direct fire and sublet launched antihelicopter mines, when properly deployed are capable of depriving attack helicopters safe ingress routes and firing positions.

DESCRIPTORS: (U) *AERIAL MINES, *HELICOPTERS, *AIR DEFENSE, ANTIAIRCRAFT DEFENSE SYSTEMS, COMPUTERIZED SIMULATION, LAND WARFARE, LAND MINE WARFARE, MILITARY EXERCISES, SMART WEAPONS MINE FIELDS, TARGET ACQUISITION, MILITARY FORCES (FOREIGN), DEPLOYMENT, KILL PROBABILITIES, AERIAL MINE WARFARE, ANTIAIRCRAFT WEAPONS.

IDENTIFIERS: (U) *Antihelicopter mines, SIMNET (Simulator Networking), Direct fire, SAF (Semi-Automated Forces).

✦ Included in *The DTIC Review*, March 1996

ADA 277803

INSTITUTE FOR DEFENSE ANALYSES
ALEXANDRIA VA

(U) The Smart Mine Simulator User's Guide and Algorithm Description

DEC 93 74P
PERSONAL AUTHORS: Schwartz, Richard E.; Carpenter, R W.; Stahl, Michelle M.
REPORT NO: IDA-D-1452
CONTRACT NO:MDA903-89-C-0003

UNCLASSIFIED REPORT

ABSTRACT: (U) The Smart Mine Simulator (SMS) is a computer simulation that runs on two UNIX workstations and operates in the SIMNET/BDS-D distributed simulation environment. It simulates smart antiarmor mines, two variations of smart antihelicopter mines, and conventional antiarmor mines enabling these mines to participate in SIMNET exercises for analytic, training, demonstration, or other purposes. This document describes the SMS structure, its algorithms for simulating mines, and how to install and use it. The document is intended to support both the planning of distributed simulation exercises and the installation and operation of the SNS on simulation networks.

DESCRIPTORS (U) *MINE FIELDS, *LAND MINE WARFARE, LAND MINES, COMPUTERIZED SIMULATION, BATTLEFIELDS, TARGET ACTIVATED MUNITIONS, ANTIARMOR AMMUNITION, MILITARY EXERCISES, USER MANUALS, MILITARY TRAINING, TARGET ACQUISITION, LAND WARFARE, SMART WEAPONS.

IDENTIFIERS: (U) Antihelicopter mines, Smart ammunitions, Wide area mines, SIMNET (Simulation Network).

ADA 274141

ARMY TOPOGRAPHIC ENGINEERING CENTER
FORT BELVOIR VA

(U) Project Ostrich A Feasibility Study: Detecting Buried Mines in Dry Soils Using Synthetic Aperture Radar

SEP 93 108P
PERSONAL AUTHORS: Hanson, John V. ; Ehlen, Judy; Evans, Timothy D.; Hevenor, Richard A.
REPORT NO: TEC-0040

UNCLASSIFIED REPORT

ABSTRACT (U) Metallic and nonmetallic mines were utilized to construct a mine field in arid soil at Twenty nine Palms, California to assess the extent to which long-wavelength radar could be used to detect buried mines by remote sensing. Surface and subsurface mines were placed in accordance with known enemy doctrine, and the site was imaged with X-, C- and L-band radar from a Navy P-3 aircraft. This report describes the construction and physical characteristics of the test sites, and presents and discusses the results of imagery analysis.

DESCRIPTORS (U) *MINE FIELDS, *MINE DETECTION, *SYNTHETIC APERTURE RADAR, AIRCRAFT, BURIED OBJECTS, CALIFORNIA, CONSTRUCTION, DOCTRINE, ENEMY, L BAND, LONG WAVELENGTHS, NAVY, RADAR, SITES, SOILS, SUBSURFACE, SURFACES, TEST AND EVALUATION.

ADA 266171

NAVAL COMMAND CONTROL AND OCEAN
SURVEILLANCE CENTER RDT&E DIV
SAN DIEGO CA

(U) Recent Developments in Tactical Unmanned Ground Vehicles

JUN 93 9P
PERSONAL AUTHORS: Metz, C. D.; Everett, H. R.; Myers, S.
PROJECT NO: CH58

UNCLASSIFIED REPORT

Availability: Pub. in Proceedings AUVS-92, 19th Annual Technical Symposium and Exhibition, 22 Jun 92.

ABSTRACT: (U) Unmanned ground vehicles have long been envisioned in battlefield support roles involving reconnaissance, surveillance, target acquisitions and NBC and mine detection. Appropriate utilization of robotic vehicles for these tasks can be an effective force multiplier and an enhancement to soldier survivability. Over the past six years there has been substantial progress in the development of prototype unmanned ground vehicles for use by the Army and the Marine Corps. This paper looks at several versions of tactical unmanned ground vehicles and discusses technical issues with respect to remote platforms, mission modules and control units.

DESCRIPTORS: (U) *ROBOTICS, *REMOTELY PILOTED VEHICLES, *ARMY EQUIPMENT, ARMY PERSONNEL, BATTLEFIELDS, CONTROL, DETECTION, GROUND VEHICLES, MINE DETECTION, MISSIONS, PLATFORMS PROTOTYPES, RECONNAISSANCE, SURVEILLANCE, SURVIVABILITY, TARGET ACQUISITION, UTILIZATION, CHEMICAL AGENT DETECTORS, TELEOPERATORS, MILITARY RESEARCH, TEST AND EVALUATION, PERFORMANCE (ENGINEERING), STEREOSCOPIC DISPLAY SYSTEMS, CONTROL SYSTEMS, FIBER OPTICS, TRANSMISSION LINES, REPRINTS.

IDENTIFIERS: (U) TOV (Teleoperated Vehicle), STV (Surrogate Teleoperated Vehicles), Unmanned ground vehicle, Head mounted displays.

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